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Extended System Operations Studies for Automated Guideway Transit Systems

Procedure for the Analysis of Representative AGT Deployments

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DEPARTMENT OF
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16. Abstract

A major output of the Systems Operations Studies (SOS) -- one segment of the UMTA Automated Guideway Transit Technology (AGTT) program -- is a set of comprehensive computer models which support the analysis of automated guideway systems. The purpose of this report is to present a general procedure for using the SOS software to analyze AGT systems. Data to aid the analyst in specifying input information, which is required as input to the software, are summarized in appendices. For the most part, the data are based on analyses of information derived from existing and proposed systems during the SOS program. The procedure described in this report is based on experience gained during the SOS program and from other applications of the SOS software.

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PREFACE

The Automated Guideway Transit Technology (AGTT) System Operations Studies (SOS) program, sponsored by the Urban Mass Transportation Administration (UMTA), resulted in a comprehensive set of AGT system planning and development models. In order to maximize the benefits resulting from the availability of these models, GM Transportation Systems Division (GM TSD) was awarded a contract by the Transportation Systems Center of the U.S. Department of Transportation. The objectives of this effort are to enhance the usefulness of the AGTT-SOS software through continued research and development activity, to increase user familiarity of, and confidence in, the software through information dissemination workshops and validation, and to extend the guideline standards and requirements for analysis of AGT systems.

This report presents a general procedure for using the SOS software to analyze AGT systems. The procedure is based on experience gained from actual use of the software during the System Operations Studies and other applications of the software. Data to aid the analyst in specifying input information are summarized in appendices.

This document was prepared under the direction of the Extended SOS Program Manager at GM TSD, James F. Thompson. Final preparation of the report was the responsibility of Ronald A. Lee of GM TSD. James D. Boldig, Michael J. Rizzuto, and Gary Sullo contributed to the report in the areas of system availability, station design, and system costs, respectively.

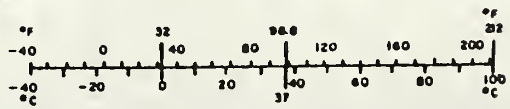
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ACRONYMS

A/C	Air Conditioning
ACT	Automatically Controlled Transit
AGT	Automated Guideway Transit
AGRT	Advanced Group Rapid Transit
AGTT	Automated Guideway Transit Technology
APL/JHU	Applied Physics Laboratory/Johns Hopkins University
ART	Automated Rail Transit
BART	Bay Area Rapid Transit
CBD	Central Business District
CHAR	(Feeder System) Characteristics (File)
COP	Comparison Output Processor
CVS	Computer Controlled Vehicle System
DDP	Deterministic Demand Pre-processor
DESM	Discrete Event Simulation Model
DM	Dual Mode
DMTS	Dual Mode Transit System
DOCM	Detailed Operational Control Model
DOT/TSC	Department of Transportation/Transportation Systems Center
DPMS	Downtown People Mover Simulation
DSM	Detailed Station Model
DZZ	Zone-to-Zone Demand (File, Feeder System Model)
FIFO	First In First Out
FMEA	Failure Modes and Effects Analysis
FSM	Feeder System Model
GM TSC	General Motors Transportation Systems Center
GM TSD	General Motors Transportation Systems Divison
GRT	Group Rapid Transit
GVMP	Guideway Vehicle Motion Program
IANDD	Input and Description (File)
IGRT	Intermediate (Capacity) GRT
KCV	Kawasaki Computer-Controlled Vehicles
KRT	Kobe Personal Rapid Transit
LGRT	Large (Capacity) GRT
LUDP	Link Utilization Display Program
MARTA	Metropolitan Atlanta Rapid Transit Authority
MAT	Mitsubishi Automatic Transportation System
MTBF	Mean Time Between Failure
NBM	Network Build Module
NIA	Noise Impacted Area
NTS	Newtran System
O/D	Origin/Destination
PARAFOR	Structured Superset of Fortran
PQLDP	Passenger Queue Length Display Program
PRT	Personal Rapid Transit
RNTIM	Runtime (File)
SAM	System Availability Model
SCM	System Cost Model
SCMEQU	System Cost Model Equation (File)
SCMCOM	System Cost Model Common (Data File)
SCMDPLY	System Cost Model Deployment (Data File)
SCMSYS	System Cost Model System (Data File)

SEMTA	Southeastern Michigan Transportation Authority
SGRT	Small (Capacity) GRT
SLT	Shuttle Loop Transit
SOS	System Operations Studies
SPM	System Planning Model
SSP	Station-to-Station Performance (File, Feeder System Model)
STRUC	Structured (Data File)
UMI	Universal Mobility Incorporated
UMTA	Urban Mass Transportation Authority
VONA	Vehicles of New Age
WMATA	Washington Metropolitan Area Transit Authority
ZN	Zone File (Feeder System Model)

1.0 INTRODUCTION

A major output of the System Operations Studies (SOS) -- one segment of the UMTA Automated Guideway Transit Technology (AGTT) program -- is a set of comprehensive computer models which support the analysis of automated guideway systems. The computer programs, written in structured Fortran, were developed primarily to serve the analysis needs of the System Operations Studies. However, the software has proved to be useful in other analyses as well. The purpose of this report is to present a general procedure for using the SOS software to analyze AGT systems. In order to represent an AGT system for simulation, system description data are required as input to the software. Data to aid the analyst in specifying this input information are summarized in appendices to this report. For the most part, the data are based on analyses of information derived from existing and proposed systems during the SOS program. The procedure described in this report is based on experience gained during the SOS program[1] and from other applications of the SOS software.[73-76]

In this section potential applications of the SOS software are discussed in terms of the deployment characteristics which can be evaluated using the SOS models. Then, a brief description of the functions of each SOS model is presented. Section 2.0 provides an overview of the analysis procedure, and the remaining sections of this report detail each major portion of the procedure. Appendices are included which not only present data developed during the System Operations Studies to support system analysis, but also provide more detailed descriptions of certain analysis procedures.

1.1 USES OF THE SOS SOFTWARE

The SOS software can be used to simulate the operation of an entire AGT system deployment or to evaluate the detailed operation of particular guideway segments and stations. The software can also be used to evaluate life cycle costs, system availability, and feeder system requirements. The software permits the detailed modeling of a wide variety of system configuration and operations alternatives. Specifically, networks ranging from simple loops and shuttles to complex grids can be evaluated in terms of

relative area coverage, potential congestion, and overall system operation. System design parameters such as vehicle capacity, fleet size, route headway, cruise velocity, and minimum headway, can be evaluated. Service policy alternatives including various fixed routes with scheduled or demand stops and various demand responsive policies can be analyzed. The operation of several empty vehicle management alternatives can be investigated in conjunction with demand responsive service. The sensitivity of system performance to demand variations and the sensitivity of system cost to unit cost variations can be easily evaluated using the software. The impacts on system availability of alternate failure management strategies and variations in subsystem reliability can be analyzed. Operational control alternatives such as synchronous versus asynchronous vehicle control, first in first out (FIFO) versus priority merge strategies, and fixed versus dynamic entrainment policy can be evaluated on the system level. The stability and performance of alternative control algorithms operating in the face of non-uniform vehicle characteristics can be investigated. The detailed operation of individual stations can be analyzed including evaluation of alternative platform configurations, vehicle queue requirements, and dwell time.

The emphasis which is placed on these possible evaluations obviously depends on the context of the overall analysis. The software was originally designed to support the analysis of generic AGT systems deployed in representative applications. The purposes of the SOS analyses were to quantify the performance and cost characteristics of a variety of AGT system deployments to serve as a basis for future decision-making and to develop design guidelines to aid in future analysis and design of AGT systems. The SOS analyses were structured to test a variety of system characteristics and service policies in several different hypothetical applications.

Another application for the SOS software is to support feasibility studies or preliminary engineering of AGT systems which may be actually deployed in specific locales. The same sort of analyses which were conducted under the System Operations Studies are required to support this type of analysis, but more detailed consideration of site-specific constraints on the deployment is necessary. The SOS models, especially the

Network Build Module, the Feeder System Model, and the Discrete Event Simulation Model, are particularly useful in the evaluation of alternative route alignments. The Network Build Module (NBM) greatly facilitates the process of coding alternative networks for input to the software. The Feeder System Model (FSM) can be used to provide a coarse measure of relative demand attraction for the purpose of initially screening the network alternatives. The Discrete Event Simulation Model (DESM) can provide detailed performance measures for input to a modal split model and for technical evaluation of route alignment alternatives. Evaluations of impacts on system performance and cost of various system characteristics can also contribute to the development of system specifications.

A third potential application for the SOS software is in the assessment of existing AGT systems and in the evaluation of proposed system modifications. The software can be used to estimate service characteristics, such as average wait time and travel time, which cannot be easily measured in the actual system. If actual performance data are available, the data can be used to calibrate the model of the system so that the DESM can be used with greater confidence to predict system performance under alternate operational strategies. The alternate strategies may include a different routing structure, different route headways or consists, and demand stop or demand responsive service policies. The software can also be used to evaluate the performance consequences and system requirements associated with a network expansion or system capacity expansion to accommodate increased demand.

1.2 FUNCTIONAL DESCRIPTION OF THE SOS MODELS

The set of computer models developed during the AGTT-SOS program supports the evaluation of AGT deployments on the system level as well as on the subsystem level. Support software has been provided to help simplify the user interface. The computer programs themselves fall into four major categories:

1. Subsystem performance simulation and evaluation
    - Detailed Station Model (DSM) - A detailed simulation of the movement of vehicles and passengers in a station
    - Detailed Operational Control Model (DOCM) - A detailed simulation of vehicle movements on a link and through a merge or intersection

- Feeder System Model (FSM) - A model of feeder system operation used to estimate the trips served by an AGT deployment out of a total set of transit oriented trips in an area.

2. System Performance Simulation
   - Discrete Event Simulation Model (DESM) - A detailed simulation of the movements of individual vehicles and passengers throughout an AGT network using discrete event simulation techniques
   - Downtown People Mover Simulation (DPMS) - A modified version of the DESM providing a direct interface with UTPS
   - System Planning Model (SPM) - A coarse flow model of AGT vehicles and passengers on links and in queues.

3. System Availability and Cost Evaluation
   - System Availability Model (SAM) - An analytic model using equipment failure rates and simulated operations data to evaluate system availability.
   - System Cost Model (SCM) - An analytic model using unit costs, deployment configuration, simulated operations data, and economic factors to calculate capital, operating, and life cycle costs.

4. Analysis Support Software
   - A set of support programs which provide for graphic network input (NBM), dynamic display of vehicle motion, queue lengths and link loading (GVMP, PQLDP, and LUDP), nonstochastic demand input generation (DDP), comparison of summary statistics (COP), and preprocessing of structured Fortran (PARAFOR).

A brief description of the functions of each processor is presented in the AGTT-SOS Summary Report.[1] However, to gain a more complete appreciation of the capabilities and limitations of the software, a thorough examination of the software functional specifications is recommended (References 2-8). User's Manuals (References 9-17) provide the detailed information required to use the software such as the definition of input/output parameters and formats, computer requirements, and operating procedures.

2.0 OVERVIEW OF THE ANALYSIS PROCEDURE

The design of an AGT system, even in conceptual terms, involves the specification of a great many system parameters. While it may be useful to consider a range of values for most design parameters and several alternative operating strategies, it is usually not practical to investigate all possible combinations of parameter values in a trade-off analysis. In order to limit the scope of the analysis, the parameters can be grouped into three categories which relate to different levels of design specification. Alternative values of parameters within each category can be evaluated somewhat independently. Thus, the consideration of parameters within each of the three categories corresponds to a separate phase in the analysis of an AGT system deployment. The three phases of analysis which are described in this procedure are initial system definition and screening, trade-off analyses, and sensitivity analyses. Initial system definition involves the specification of basic system parameters which define alternative system concepts. Trade-off analyses involve the evaluation of other system parameters which represent major alternatives within a given system concept. Sensitivity analyses involve the evaluation of the system level impacts of variations in still other system parameters.

While several tasks are completed under the initial system definition phase of the analysis, the main objective is to identify deployment alternatives which merit further analysis. Deployment alternatives are initially defined in terms of basic parameters such as vehicle class (Personal Rapid Transit (PRT), Small Vehicle Group Rapid Transit (SGRT), etc.), service policy, and network configuration. Deployment alternatives are screened during this phase of the analysis to limit the number of different deployments to be analyzed in subsequent analyses.

One of the tasks of initial system definition is preliminary analysis to define application areas, demand, networks, and routing strategies for scheduled service. If a specific application of AGT technology is to be evaluated, data which describes the site-specific details of the application area must be collected. If the analysis is of a more generic nature, then a less detailed description of the application area will suffice. The procedure that was followed in the System Operations Studies to select and

define representative application areas for analysis is presented in an SOS report.[18] A procedure for using the SOS software to define and model candidate networks is described in Section 4.0. A procedure for estimating AGT demand using the SOS software is presented in Section 3.0.

Another major task of the initial system definition process is the analysis of major subsystems to determine characteristics and relationships necessary to support the system analysis. Guidelines for the definition of major subsystems are presented in appendices to this report. Appendix B presents data and equations for calculating characteristics of AGT vehicles such as dimensions, performance, energy utilization, and noise generation. Equations for calculating minimum headway and a procedure for estimating control system cost parameters are presented in Appendix C. Alternative operational control strategies which can be modeled using the SOS software are also briefly defined. A detailed analysis of the subsystem and system level impacts of alternate control strategies is presented in an SOS report.[19] Guidelines for sizing AGT stations, derived from analysis using the Detailed Station Model (DSM) and the Discrete Event Simulation Model (DESM), are presented in Appendix D. The cost model which has been implemented in the SOS software (System Cost Model) is discussed, and representative cost data are presented in Appendix E. Appendix F presents a procedure for conducting an availability analysis including the generation of subsystem reliability data, the selection of representative failure events, the evaluation of failure consequences using the DESM, and the evaluation of system availability using the System Availability Model (SAM). Appendix G contains data from an SOS availability analysis to help illustrate the procedure.

Once the reference data and relationships have been generated and alternative system deployments have been initially defined, the final step of this first phase of analysis, deployment screening, can be completed. A procedure for quickly evaluating system deployments is presented in Section 6.0. The purpose of this initial screening is to limit the scope of subsequent more detailed analyses by eliminating from further consideration deployment alternatives which are clearly inferior.

The second category of system design parameters includes those which represent major alternatives within a given system concept. These secondary parameters include empty vehicle management strategies for demand responsive service and the number of cars per train by route for scheduled service. The effects on system performance, cost, and demand of alternative values of parameters in this category are evaluated in trade studies. These trade studies constitute the second phase of system analysis. The output of this phase of the analysis is a set of system deployments which satisfy performance requirements in a cost effective manner. The systems are well defined in terms of performance, cost, and availability characteristics. Guidelines for conducting system trade-off analyses are presented in Section 7.0.

The third category of system design parameters consists of a relatively large number of parameters which are amenable to independent variation within a narrow range of values. These parameters, which include cruise speed, dwell time, vehicle capacity, and unit cost values, are varied parametrically in a sensitivity analysis to characterize their impacts on system performance and costs. The results of these sensitivity analyses, the third phase of system analysis, are then applied to define an improved configuration for each of the system deployments under investigation. This third phase of system analysis is described in Section 8.0.

Figure 2-1 illustrates the manner in which the SOS processors are used to support system analyses. The figure also shows the general flow of data from one part of the analysis to another. Each of the three stages of analysis includes some or all of the analyses depicted in Figure 2-1. Initial system definition and screening includes demand generation and subsystem analysis and a limited amount of performance analysis. The second phase of analysis, system trade-offs, includes performance, cost, and availability analyses. It also includes an iteration of the demand generation process. The performance, cost, and availability processors are all used in the sensitivity analysis. The following discussion identifies, in general, how the SOS software is used to support each phase of the analysis.

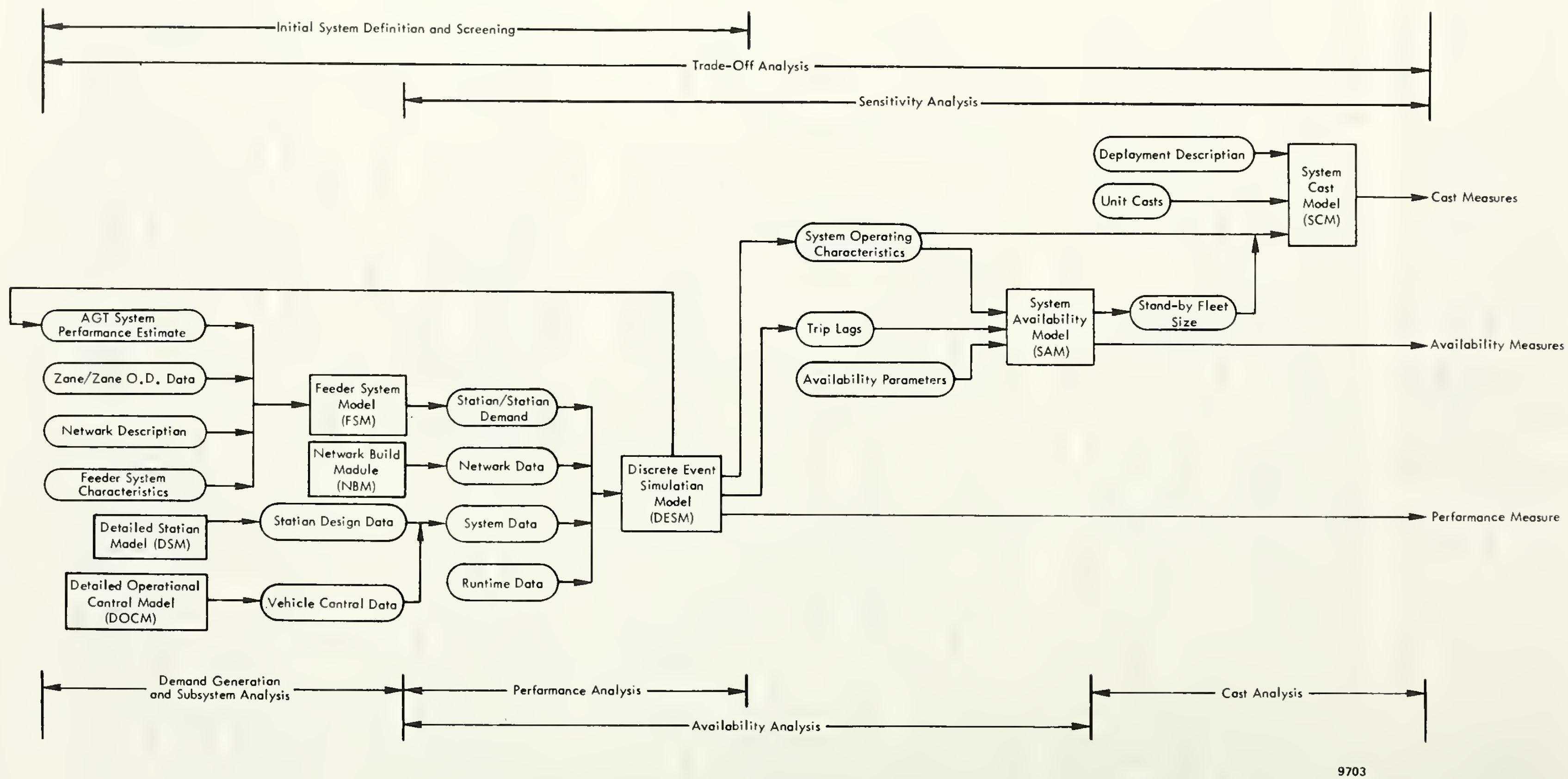

FIGURE 2-1. USE OF AGTT-SOS SOFTWARE FOR SYSTEM ANALYSIS

Initial system definition begins with demand generation and subsystem analysis. After a set of deployment concepts have been identified, the Feeder System Model (FSM) is used to generate station-to-station demand matrices for each deployment. Inputs to the FSM include zone-to-zone origin-destination demand data, a network description in terms of station coordinates relative to zone centroid locations, feeder system characteristics, and an estimate of station-to-station trip time for the deployment under consideration. The Input Processor of the DESM generates the AGT system performance estimate in the form of the AGT.IANDD.SSP file. Before this file is input to the FSM, the analyst must add to each entry an estimate of initial wait time at the AGT stations. The output of the FSM includes station-to-station demand matrices for all demand periods. These matrices serve as direct inputs to the Discrete Event Simulation Model (DESM).

The network decription used in the Feeder System Model (FSM) for demand generation can be converted to DESM input with the aid of the Network Build Module (NBM). This interactive graphics program accepts station location and network connectivity data and produces the network file which is input directly into the DESM.

The Detailed Station Model (DSM) is used in the subsystem analysis to investigate flows and queues of both vehicles and passengers in on-line or off-line stations.

The Detailed Operational Control Model (DOCM) is used in another subsystem analysis to evaluate minimum headway requirements and vehicle control alternatives.

The results of the subsystem analyses are used in the development of system data for input to the DESM. The DESM evaluates performance measures which are used in screening the deployments to identify the ones which have potential for satisfying system goals and are worthy of more detailed analysis.

In the trade-off analysis, the DESM is run a number of times for each deployment to determine the combinations of vehicle capacity, train consist, and operating headway which satisfy the wait time and performance goals for each major demand period of the service day. The size of the operating vehicle fleet is the major independent variable in the process of matching the performance of each deployment with the performance goals. The system configuration which satisfies the performance goals at approximately minimum cost is selected as the nominal configuration for each deployment. System costs are evaluated using the System Cost Model (SCM). In addition to capital and variable costs, the SCM also evaluates land utilization, energy consumption, and air pollution. Required inputs to the SCM include system operating characteristics based on DESM outputs, standby fleet size generated by the System Availability Model (SAM), and system description and unit cost information supplied by the analyst. Trade-offs of major system parameters are made by comparing performance and cost measures for the nominal deployments. In this way the overall system effects of various parameters are considered in each trade-off. If the performance of the nominal system is significantly different from that initially estimated, the demand generation process is repeated using the best available estimates of system performance. Then, using updated demand estimates, system sizing and performance analyses are repeated to define nominal system characteristics.

The availability analysis involves the use of both the DESM and the System Availability Model (SAM) to evaluate the consequences of failures on system performance. Since the availability analysis is a rather involved process, a limited number of deployments should be selected for analysis based on cost and nominal performance measures. The DESM is used in the availability analysis to generate vehicle and passenger delay information relating to various failures. A trip log (a file containing a record for every completed trip) is generated by the DESM and used as direct input to the SAM to evaluate the number of passengers delayed by individual failures. Output statistics generated by the DESM are used by the analyst to calculate vehicle delay data and system operating characteristics for input to the SAM. The SAM also requires as input availability parameters such as failure rates and mean time to repair. The SAM generates measures of system availability and the standby fleet size required to achieve those values of availability.

Some sensitivity data can be generated by varying the values of input parameters for each processor independently. For example, the sensitivity of system costs to variations in unit costs can be evaluated with the SCM; the sensitivity of system availability to variations in subsystem reliabilities can be evaluated with the SAM. In other cases, however, changes in system parameters must be evaluated in terms of their effects on performance, cost, and availability. This involves the combined use of the DESM for performance evaluation, the SCM for cost evaluations, and the SAM for availability evaluations. For example, if the variation in system parameters causes variations in the consequences of failures, then an evaluation of failure consequences using the DESM must precede the use of the SAM to evaluate system availability. Those parameter variations may also result in system cost variations which would be investigated using the SCM. Once generated, the sensitivity data are used to specify improved system deployments and to represent the performance, cost, and availability of a range of system configurations based on each deployment.

3.0 DEMAND

An estimate of the patronage is one of the most important inputs to the analysis process. Not only is the design itself highly dependent on the spatial distribution of demand as well as its magnitude, but critical comparative measures such as total cost and cost per passenger are also quite dependent on the design demand. The level and distribution of demand used to specify system design and performance characteristics must bear a reasonable relationship to that which would actually be attracted to the system. Otherwise, the analysis results are not credible. In view of this need, an accepted modal split model should be first calibrated, then applied to each deployment alternative to generate station-to-station demand matrices. For some applications, especially metropolitan areas, the modal split process which is supported by the UTPS package can be used to estimate demand provided sufficient data and project resources are available. In other applications, such as activity centers, the Cambridge Systematics model[20] may be appropriate. Both of these mode split processes utilize a multi-nomial logit representation of mode choice and require a great deal of site-specific input data. An alternative approach, which requires less data and fewer resources, is to use the AGTT-SOS Feeder System Model (FSM) to map zone-to-zone demand onto the various AGT networks. The Feeder System Model assigns zone-to-zone demand to a station-to-station pair in proportion to the ratio of trip time via an alternate mode to the sum of trip times via the alternate mode and the AGT system. While this is a very simplistic diversion function which should not be used for detailed patronage analysis, the use of the FSM does offer several advantages over the use of a more complex modal split model for analyses of a generic nature. First, like a more complex model, the FSM is sensitive to variations in network configuration, network operation, and network area coverage. Second, the input data required by the FSM are not nearly as extensive as the input required by many modal split models. The FSM requires the following data as input to the demand processing functions:

- zone-to-zone demand matrices
- zone and station coordinates
- average velocity of off-guideway travel for both access to AGT stations and access to other zones via an alternate mode.
- station-to-station trip times for guideway travel

Finally, the FSM is compatible with the SOS performance simulation -- the DESM. The station-to-station trip times are generated by the Input Processor of the DESM in a format which can be input directly into the FSM, and conversely, the station-to-station demand matrices are generated by the FSM in a format which can be input directly into the DESM.

While the estimation of zone-to-zone travel demand data is considered to be beyond the scope of the analyses defined in this procedure, at least two approaches can be used to obtain reference demand data for input to the FSM. One approach for metropolitan areas is to use an abstract representation of demand based on average demand densities which vary inversely with proximity to the CBD and to assumed high density corridors. An approach similar to this was used by Benjamin [21] to produce the travel demand for Plastictown, a hypothetical 1990 city. Another approach is to use transportation survey data from an actual city or activity center. In the AGTT System Operations Studies project, travel survey data from Detroit, Cincinnati, and Washington, D.C., which are representative of several metropolitan demand types, were used to generate zone-to-zone travel demand matrices for representative application areas. Zone-to-zone demand matrices for other application areas can be generated from survey tapes, if available, using the general process described in the AGTT-SOS report "Representative Application Areas for AGT."[18]

For purposes of analysis using the DESM, demand is represented in terms of both station-to-station demand matrices, which describe the spatial distribution of demand for various periods during the service day, and a demand profile, which defines variations in demand magnitude within each demand period. The spatial distribution and the time profiles can be treated as independent parameters and varied separately in the analysis. The demand matrices can be generated by the FSM. The demand profiles are specified by the analyst and can be easily varied parametrically to permit the evaluation of a range of demand magnitudes and peaking characteristics. The demand matrices are input as members of the Input and Description Demand file. This is a fixed format file which identifies the number of stations in the network, the time base in minutes for which the demand matrix

applies, the origin to destination demand data, and the trip size distribution data. The trip size distribution data defines the probability that passengers arrive at stations and travel together in groups of from one passenger to the maximum group size. A trip is defined, then, as a number of passengers traveling together by choice.

As a compromise for computational purposes, four demand matrices are usually considered: a.m. peak, midday, p.m. peak, and evening. As a minimum, a peak period matrix and an off-peak period matrix should be specified so that daily performance and costs can be estimated.

For input to the Model Processor of the DESM, the demand data must be converted into a trip list which includes the following information for each entry in the list:

1. Origin Station
2. Destination Station
3. Number of Patrons in the Trip
4. Time of Arrival at the Origin Station

If the trip list is not generated by an external process, the Input Processor of the DESM generates one according to a compound Poisson process. The result is one sample from a random trip generation process. Trip lists generated in this manner are useful as driving functions to test the performance of an AGT system. However, some undesirable results were obtained during the System Operations Studies when a single, randomly-generated trip list was used in the system design process (i.e., in analyses to specify system capacity). In that study, system capacity was specified to just satisfy the demand at each station. When system performance was tested against a variety of different trip lists, the result in some instances was poor performance characterized by long passenger queues and unacceptable wait times at the most congested stations. It was discovered that while the randomly generated trip lists closely replicated the average total demand, sometimes the particular trip list used in the design process understated the demand for a critical station in the network. As a result, when another trip list was used which did not understate the demand for the critical station, system capacity was not sufficient to adequately serve the demand.

Since any given trip list is only one sample of a compound Poisson process, the demand for particular station pairs may be significantly above or below the average value represented by the matrix. Therefore, a single randomly-generated trip list should not be used as the basis for a system design. Two alternatives to using such a trip list are as follows:

1. Use a statistically significant number of randomly-generated trip lists to test each alternative in the design process
2. Use one deterministically-generated trip list for system design purposes; then test system performance using a number of randomly-generated trip lists.

Because the first alternative is quite time consuming and costly, the second alternative is recommended. The SOS utility program, Deterministic Demand Pre-Processor (DDP) can be used to generate uniformly distributed trip lists. Trip lists generated using a deterministic process represent the average demand for each station pair. The interarrival time of trips for each station pair is constant as long as the average arrival rate remains constant. Since the performance of AGT systems is sometimes quite sensitive to increases in demand, it is recommended that the design demand be increased by 5 to 10 percent over the nominal demand derived using the Feeder System Model. If this procedure is followed, then the performance of the resulting AGT system will not be significantly reduced if random variations in demand result in increased demand at critical areas of the network.

Since it is usually impractical to simulate an entire day of system operation, the following procedure is presented for estimating daily values of certain measures such as vehicle hours of operation, vehicle kilometers traveled, and vehicle energy consumption. In order to define system parameters, system simulations are conducted for one or more peak periods to define system capacity requirements and for one or more off-peak periods to define service characteristics during low demand periods. Measure values obtained for each statistical period (period over which simulation statistics are collected) can be assumed to be proportional to the values for the entire demand period represented by each simulation. In the case of

scheduled systems, service characteristics such as active fleet size and train consists are assumed to remain constant throughout each demand period. Daily values for the measures listed above are computed as the sum for all demand periods of the product of the value of the measure for the statistical period and the ratio of the number of hours in the demand period to the number of hours in the statistical period. In the case of demand responsive systems, the active fleet size can be assumed to vary each hour in direct proportion to the demand. For demand responsive applications, daily values for the measures listed above are computed as the sum for all demand periods of the product of the value of the measure for the statistical period and the ratio of the number of passengers in the demand period to the number of passengers in the statistical period. For both cases the number of passenger kilometers traveled per day is calculated as the sum for each hour of the day of the product of demand and average trip distance.

4.0 CANDIDATE NETWORKS

One of the most challenging and controversial tasks associated with preliminary engineering for an actual application of automated guideway transit is the specification of the guideway alignment including station location, line location, and network connectivity. The task requires detailed analysis of site-specific parameters such as demand attraction potential, right-of-way availability, environmental and aesthetic impacts, cost, and, perhaps most important, preferences of community leaders and local decision makers. The selection of a final network alignment and, to some extent, the proposal of candidates for consideration lends itself more to a non-partisan political process than to an analytical procedure. The relevant measures and their relative importance to the decision vary with the perspective of each decision-maker and with his perception of the objectives of the AGT system. For example, a particular decision-maker may favor an alignment which serves existing land uses, while another may prefer an alignment which tends to promote development. One decision-maker may favor an alignment which offers a viable alternative to private transportation, while another may prefer one which complements and promotes the use of the existing transportation infrastructure. Still other decision-makers may seek different solutions which accomplish all of these objectives and others as well. Because of the political nature of the network alignment selection process, no acceptable, rigorous, analytical procedure for proposing and then selecting network alignments seems to be possible. The role of the analyst in this activity is to translate political realities and objectives into proposed alignments which seem to satisfy the general criteria established by the group of decision-makers, and then to evaluate quantitatively each alternative. The analysts' objective should not be to reach a decision as to which alternative is superior, but rather to clarify the issues and to identify the consequences associated with each alternative. The SOS software can play a role in the evaluation of alternative network configurations once they have been proposed. However, a separate procedure, which focuses on site specific constraints, system objectives, and political realities, is required to propose candidate network designs.

4.1 DEFINITION OF NETWORK ALTERNATIVES

In more generic evaluations of AGT alternatives -- such as those which might be appropriate for feasibility studies or preliminary alternatives analyses -- a simpler, less site-specific, and less political procedure for defining candidate network alternatives can be applied. One measure of the suitability of a network alignment to an application is the passenger attraction potential of the proposed station locations. The demand attraction potential of a proposed station site is a function of the travel demand within a certain radius of the station; i.e., the travel demand density of the zone which contains the station site. If stations are located so that they serve the zones with the highest demand density, then the resulting network configurations are likely to serve the application area reasonably well. Therefore, one suggested network definition procedure begins with ranking the zones in descending order of the sum of trip production density and trip attraction density. Station locations are then specified so that the centroids of zones with the highest sum of production and attraction densities are within a given distance (e.g., .4 km) of a station. Zones with the largest trip production density and ones with the largest trip attraction density tend to be included in the list of zones with the highest sum of production and attraction density. In application areas where all zones are approximately the same size, demand magnitude may be considered in this process rather than demand density. However, in metropolitan area applications, zones located furthest from the central business district tend to be the largest in area. Because of their size, these large zones often account for a relatively high level of total demand. A station located in one of these larger zones would not necessarily attract as much demand as a station located in a smaller zone which has a higher density of trip making activity. Therefore, it is more useful to consider demand density than total demand magnitude in metropolitan area applications. Another characteristic of metropolitan area applications is that zone pairs which exhibit the highest demand magnitudes tend to be large outlying zones which are often adjacent to each other. Consideration of these high-demand zone pairs does not reveal the largest potential transit market for a metropolitan system which is usually trips to and from the CBD. Since CBD zones are small, they are rarely one of a high demand zone pair in an area wide application. However, the CBD zones taken as a whole are usually the largest attractors of a.m. peak period trips.

Once the zones which comprise the application area have been ranked according to demand density, or demand magnitude for activity center applications having essentially constant zone areas, then station locations can be identified so that centroids of the zones with the highest demand densities are within the sphere of influence of the stations. Depending on the size of the application area and the desired station spacing, the sphere of influence of stations can be defined as a radius in the range of from less than 0.4 km to more than 1.0 km. Since the guideway alignments will typically be along existing streets, stations should also be located along existing streets.

When the desired number of stations has been located, alternative network configurations connecting the stations can be proposed according to the following guidelines.

- Lay out the guideway along existing streets or rail rights-of-way to minimize right-of-way acquisition requirements
- Avoid the use of complete interchanges from one dual lane guideway segment to another to minimize the complexity and right-of-way requirements of guideway structures.

4.2 MODELING OF NETWORK CONFIGURATIONS

For the purpose of DESM simulation, networks are represented as a series of unidirectional links defined by an entry node, an exit node, the link length in meters, and a code which indicates whether or not a station is located on the link. This information is listed in a fixed-format input data file -- the Input and Description Network file. Four links are defined in each row of the file. The four numbers which identify each link represent (1) link entry node number, (2) station identification code (1 = station located on the link, 0 = no station), (3) link exit node number, and (4) link length in meters. Network connectivity is inferred by the DESM Input Processor by noting that the exit node of one or two links is the entry node for one or two other links. Two links which have the same exit node are the upstream links in a merge, while two links which have the same input node are the downstream links in a diverge. Station numbers are inferred by the Input Processor of the DESM by the relative position in the

Network file of links on which stations occur. For example, station number one is the first station identified in the network file. It is convenient to list all of the station links first in the network file, to ensure that stations are listed in the proper order. Network data is processed by the Input Processor most efficiently if links are listed in the order in which vehicles travel over them. In other words the unidirectional guideway links should be listed so that vehicles travel from link 1 to link 2 to link 3, etc.

The specification of network configurations for use with the DESM is limited by the network definition requirements listed in Table 4-1.

TABLE 4-1. DESM NETWORK DEFINITION REQUIREMENTS

- Guideway and station links are unidirectional
- Networks are fully connected
- Guideway nodes can serve as link exit nodes for at most two links
- Guideway nodes can serve as link entry nodes for at most two links
- Station entry nodes cannot serve as network merge or diverge nodes
- Station exit nodes cannot serve as network merge or diverge nodes
- Link capacity, which is a function of link length, minimum headway distance, and vehicle length, must be equal to or greater than the number of cars per train.

The first requirement is that guideway and station links be unidirectional. As a consequence of this requirement, shuttle networks must be modeled as loops. A requirement of the DESM minimum path algorithm is that networks be modeled as being fully connected. That is, a vehicle path must exist from each node to every other node in the network. It is sometimes necessary to include extra links in the model of a network to satisfy this requirement. For example, a simple Shuttle Loop Transit (SLT) network might consist of two independent loops. While routes can be specified so that vehicles operate independently on the two loops, guideway links must be provided which connect the two loops to complete the network connectivity. While these connecting links would not be used in the course of providing normal service, they may be used for active fleet size changes or for failure management.

The next two network definition requirements listed in Table 4-1 are restrictions that relate to the manner in which network connectivity is modeled. Network connectivity is limited to two links merging into one and one link diverging to two. If the actual network configuration calls for three or more links to merge into one link, this must be modeled as several two-into-one merges. Modeling merges and diverges in this way introduces no inaccuracies, but it does require one additional link for each line greater than two which merges or diverges at a single junction. The use of additional links to represent a given distance between stations or network junctions obviously results in shorter links. The modeling of short links is limited by the last requirement listed in Table 4-1, and the effects are discussed later in this section. The next two requirements listed in Table 4-1 are further restrictions on link connectivity. A station entry node (the entry node of a link on which a station is located) cannot serve as either a network merge or diverge node. To allow for the possibility of off-line stations, station entry nodes are modeled as diverge nodes. Thus, according to the previous restriction, they cannot also serve as a network diverge. Similarly, a station exit node (the exit node of a link on which a station is located) cannot serve as either a network merge or diverge node. These restrictions sometimes require that extra nodes and links be introduced in order to model network configurations with merges and diverges whether they are actual network elements or are merely required to complete the connectivity of the network model. As an example, Figure 4-1 illustrates a double-loop network configuration and three alternative models of that network. In the actual configuration, station 3 is a center platform station serving vehicles on both separate loops. Station 3 can be modeled as a single station with two berth lanes or as two separate stations. The single-station model illustrated in Figure 4-1 is the simplest model having the fewest nodes and links. This model requires that vehicles share the same guideway facilities in the vicinity of station 3 rather than operate on separate guideways. To reduce the probability that a simulated merge conflict will occur between vehicles actually operating on separate loops and to minimize the merge delay should a conflict occur, the minimum headway on the common links should be specified as a very small value (e.g., one second). Station 3 should be defined as having two berth lanes to permit vehicles from both loops to board and deboard passengers

simultaneously. The need to share links and to specify short minimum headway on some links can be avoided by modeling Station 3 as two separate stations as illustrated by the second and third models of the network in Figure 4-1. In order to use these models, the origin and destination demand for the central station must be correctly allocated to Stations 3 and 4 by editing the input demand matrix. In all of the network models, additional nodes and guideway links have been added as required to complete the network connectivity and to avoid the use of station entry and exit nodes as merges or diverges.

The final network modeling requirement listed in Table 4-1 deals with a constraint on the relative values of link length, minimum headway distance, vehicle length, and train consist. The DESM Input Processor uses the link length, minimum headway time, vehicle length, and cruise velocity to calculate a capacity for each link. The capacity of each link must be at least as great as the largest consist which will travel the link. The integer value of the following formula gives the link capacity:

$$\text{Link Capacity} = 1 + \frac{\text{Link Length-(Minimum Headway Time*Cruise Velocity)}}{\text{Vehicle Length}} \qquad (4\text{-}1)$$

While link length and cruise velocity can be specified separately for each link, their values are often dictated by network geometry and system performance goals. Minimum headway can also be specified separately for each link. One way to ensure that sufficient capacity is provided for each link is to specify an artificially low value of minimum headway for short links. Actual vehicle spacing is monitored, compared to the specified minimum, and adjusted if necessary by delaying each vehicle as it attempts to exit each link. Therefore, the desired minimum headway is enforced on the longer links even if artificially short headways are specified on a few short links. As a result of this modeling technique, "merge delays" may actually be attributed to vehicles as they attempt to enter a longer link located downstream from the merge. A major function of the DESM is to model the total time required to travel from one station to another including delays encountered enroute. With the exception of very complex networks, a minor shift in vehicle queueing from one set of guideway links to another

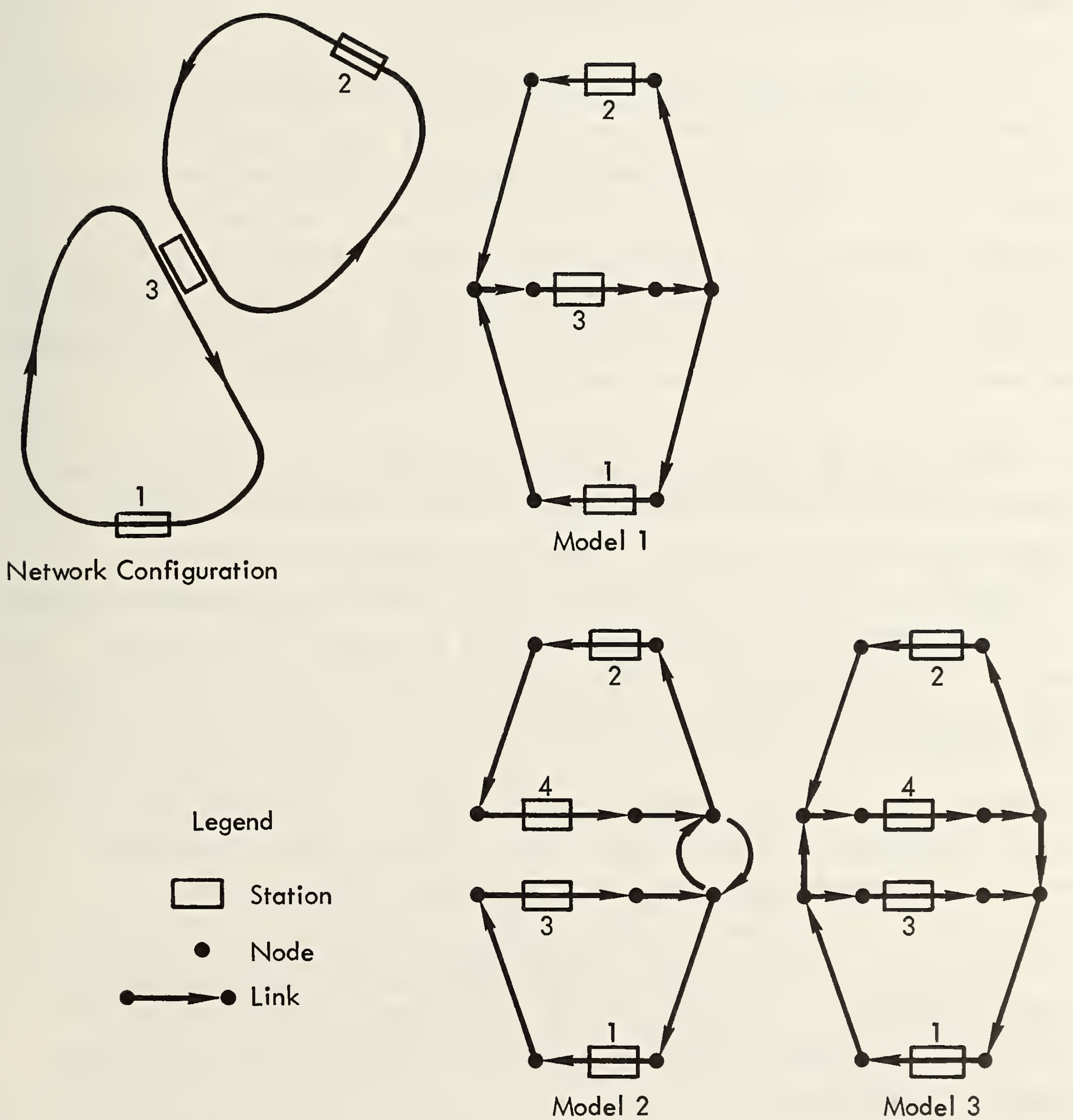

FIGURE 4-1. ALTERNATIVE MODELS OF A TWO-LOOP NETWORK CONFIGURATION

will have no appreciable effect on the overall results of the simulation. In most cases, therefore, the technique of assigning artificially short headways to short guideway links where necessary to ensure sufficient link capacity will introduce no significant errors.

In many systems, especially in the simpler SLT deployments, congestion is not a concern during normal operation because route headways are typically long compared to minimum safe headway, and the networks have few merges, if any. However, when simulating a failure condition of long duration compared to route headway, it is possible for vehicles to queue more densely if link capacity is artificially high. On the other hand, queueing of vehicles behind a failure can often be controlled by the analyst by entering additional failure events into the simulation.

Table 4-2 lists two network modeling guidelines. The first guideline states that networks should be defined so that a station is included on a given vehicle route only once. Although the DESM accepts multiple references to a station in a route definition, modeling of passenger service will be erroneous if a given station appears on a route list more than once. The route number is the only vehicle attribute which is used by the DESM to determine the destination compatibility of vehicles and passengers. As a result, if a route serves a particular station in the outbound direction as well as the inbound direction, there is nothing to prevent an outbound passenger from boarding an inbound vehicle. When this occurs, it results in overestimated travel times and tends to fill vehicles unnecessarily. One remedy for this situation is to split the station into two stations (an inbound and an outbound station) and to modify the demand matrix accordingly. The application of this guideline and of the network definition requirements listed in Table 4-1 is further illustrated by four examples in Appendix A.

The other guideline listed in Table 4-2 deals with station link considerations of network modeling. As indicated previously, the relative locations of stations are identified in the Input and Description Network file by station entry and exit nodes. The link defined by these two nodes

is interpreted as a station bypass link. The length and connectivity of guideway links (including station bypass links) are defined by the network file. The characteristics of station links for on-line as well as off-line stations are defined by the station configuration parameter in the Input and Description System file. If stations are defined in the system file as being on-line, the station bypass links are automatically made unavailable, and vehicles must travel through all stations that they encounter.

TABLE 4-2. NETWORK MODELING GUIDELINES

• Networks should be defined so that a station is included on a given vehicle route only once.
• The lengths of guideway links should be specified so that changes in station link length do not require changes in the Network file.

Since a change in the network description requires a rather inconvenient editing of the network file and reprocessing of network data by the DESM Input Processor, it is important to model the network so that frequent changes to the network file are not necessary. To avoid frequent modification of the network file, the following procedure is recommended for modeling networks with on-line stations:

- Represent the entire length of the reference network in terms of non-station guideway links (i.e., links on which no station is specified). Apportion the total distance between station pairs among the guideway links between each station pair.
- Set the length of the station bypass link equal to any convenient number which is at least as large as the length of the longest train.
- Set the time required to traverse the station input ramp equal to the difference between the time to decelerate and the time to cruise the deceleration distance at guideway link velocity. Similarly, set the time required to traverse the station output ramp equal to the difference between the time to accelerate and the time to cruise the acceleration distance at guideway link velocity.

An alternative to the first step in the procedure would be to specify the length of the on-line station "bypass" link as the sum of deceleration/acceleration distances and platform length. The length of other links between stations would be determined by subtracting the "bypass" link length from the station spacing for each station pair. However, a change in the bypass link length would necessitate a substantial modification of the network file and would require reprocessing of the network data by the Input Processor. By following the procedure outlined above, no network file modifications would be required to account for differences in acceleration and deceleration distances resulting from changes in operating speed or vehicle performance. These differences can be accounted for in the system file. Since the entire guideway length is modeled as guideway links between stations, the value of vehicle distance traveled as calculated by the DESM represents the total vehicle distance traveled including that traveled in stations. This number is useful in establishing maintenance requirements and costs. To determine the number of train kilometers traveled at cruise velocity for the vehicle energy consumption calculation, the distance traveled on station links must be subtracted from the total value. The number of train kilometers traveled on station links can be estimated as the product of the number of station entries and the sum of station acceleration and deceleration distances. The second step of the procedure results in no inaccuracies since vehicles are never routed over station "bypass" links if stations are defined as being on-line. However, it must be remembered that the true length of the guideway for cost estimating purposes differs from the sum of the link lengths in the network file. The third step in the network modeling procedure is necessary to correctly model station-to-station travel time. As indicated in the first step of the procedure, the total length of guideway in the reference network, including on-line station acceleration and deceleration lane length, is included as mainline guideway distance. As a result, the time required to travel the station acceleration and deceleration distances at the specified guideway link cruise velocity is calculated by the DESM. Since more time is actually required to complete an acceleration or deceleration maneuver than to cruise an equivalent distance at constant velocity, the additional time is included by specifying the station link traversal times as indicated in the third step of the procedure.

When stations are specified as being off-line, the station bypass links defined in the network file are actually utilized by vehicles. Their lengths cannot be specified arbitrarily, and they should approximate the distance actually required for the station acceleration and deceleration lanes, the platform, and input and output queues. Since off-line stations are actually offset from the mainline guideway and the amount of the offset is variable at least in concept, it is reasonable for the length of the station links to exceed the length of the bypass link. Thus, in most cases, the length of the bypass link and surrounding links need not be changed in the network file as station link lengths are changed during the analysis. In the case of off-line stations, the value of vehicle kilometers traveled as calculated by the DESM represents the distance traveled by vehicles on mainline guideway links at the specified cruise speed. The additional distance traveled by vehicles on off-line station links must be calculated by the analyst.

4.3 COMPUTER AIDED INPUT OF NETWORK DATA

An interactive, computer-aided method of modeling graphically-defined network configurations and entering data into pre-formatted files for use by the AGTT-SOS simulations is provided by the Network Build Module (NBM). The guideway, the station locations, and the vehicle routes are entered from a map by using a graphics tablet or from the keyboard using the joyswitch. The interactive program of the Network Build Module utilizes a Tektronix 4081 terminal. The resulting data file is transmitted to the computer used for the AGTT-SOS simulations by the Transfer Program where it is converted to standard AGTT-SOS file format by the Conversion Program. Capabilities are provided for creating new NBM files and for modifying existing files.

In order to input a network model using the Network Build Module, the user first sketches the network on a map of the application area and attaches the map to the Tektronix graphics tablet. The user then defines the coordinate system to be used by the Network Build Module to "digitize" network nodes. If zone-to-zone demand data is to be used to generate station-to-station demand matrices, then the coordinate system used to input the network should be the same as that used to define zone centroids. The

coordinate system is defined by identifying the location and coordinates of two points -- one in the lower left portion of the map to define the minimum X and Y coordinates and one in the upper right portion to define the maximum X and Y coordinates.

The user then inputs each node (station, merge, diverge, etc.) in the network by touching the sketch attached to the graphics tablet with the tablet pen. The existence and direction of guideway links are inferred by the order in which nodes are input. Bidirectional links can be input by the user, but the Network Build Module interprets them as two separate links in opposite directions. The NBM automatically splits nodes associated with bidirectional links into two separate nodes unless the node is located at the terminus of a line. The user then identifies the nodes which correspond to stations. These nodes are interpreted by the NBM as station input nodes. The NBM automatically defines a station exit node and a station bypass link for each station. Finally, the user defines the routes in terms of a cyclic sequence of station stops.

5.0 MEASURES

Measures provide a means whereby various AGT systems, operating in different deployment scenarios, can be evaluated. The measures should permit the quantitative evaluation of both the operational system attributes and the extent to which a given system design achieves desired goals. As such, the measures establish a basis for comparison of different system designs and the evaluation of system response to normal operating conditions and anomalous operating conditions such as unanticipated demand loading or subsystem failures.

Over 500 individual measures of performance, cost, and availability are evaluated by the SOS system-level models. Many of these measures have multiple values (e.g., one for each station, guideway link, route, simulation sampling interval, year in the life cycle costing period, etc.). Literally thousands of measure values can be obtained from the SOS processors and, in theory, used by an analyst to evaluate virtually any aspect of an AGT deployment. Not all of the performance measures are applicable to a given deployment, and some are more useful than others depending on the deployment and the aspect of system operation that is being investigated. As a practical necessity and to achieve compatibility among results, a subset of the available measures must be selected for consideration in a particular analysis. The subset of measures selected to compare alternative system deployments should satisfy the following requirements:

1. Completeness - the set of measures should be adequate to cover all important quantifiable aspects of the deployment.
2. Operationality - the measures should be meaningful to those who use them in the decision process.
3. Non-redundancy - the set of measures should not be redundant so that double counting of impacts is avoided.
4. Minimality - the set should be as small as possible to facilitate understanding of trade-offs.

To identify a small but adequate set of measures for consideration in system tradeoffs, deployment objectives must be defined as explicitly as possible. Often some of the primary objectives of a transit system in a specific application involve issues which place constraints on network alignment but which are not addressed by the SOS software. These objectives may include the following:

- Promote development in the vicinity of specific sites within the application area.
- Serve the transit needs of particular groups within the service area.
- Link specific land uses with quality transportation.

On the other hand, other objectives relate to very basic issues which are addressed by the SOS software. Objectives which can be used to define relevant measures for system evaluation include:

- Design feasibility
- Design efficiency
- Service effectiveness [22]

Feasibility encompasses both technical and urban integration aspects of system design. For a given network configuration, technical feasibility of a system alternative is related inversely to the degree to which the flow of vehicles on the guideway approaches the maximum theoretical flow. This can be quantified by a measure of maximum link utilization. The measure can be calculated from output of the DESM as the ratio of the maximum number of vehicles entering a guideway link per sampling interval to the theoretical maximum flow based on minimum headway. Obviously, when evaluating this measure, the modeling technique used to represent the network must be taken into account. Links which are shared by vehicles on two or more routes in the model but not in the actual network configuration should be eliminated from consideration. The maximum link utilization factor is a measure of the amount by which system capacity could be increased to accommodate an increase in demand. It also indicates where in the network congestion is likely to develop as the active fleet size is increased. The extent to

which network modifications might alleviate potential congestion can be measured by the number of links whose utilization is above a given threshold such as 70 percent of maximum theoretical capacity.

For a given network configuration, the physical size of stations has a major impact on urban integration feasibility. Station size depends on both vehicle and passenger flow through the station. A measure of vehicle capacity requirements in stations available from the DESM is the maximum number of vehicles in a station at one time. This number may include the number of empty vehicles stored in the station if appropriate. An alternate measure available from the simulation is the maximum number of vehicles entering a station during one sampling interval. Either this rate of flow or the maximum occupancy measure can be used to quantify the vehicle processing requirements of the most heavily utilized station in the network. The passenger processing requirements of stations can be expressed in terms of the maximum number of passengers waiting at any time in the most heavily loaded station. Alternatively, the ratio of the maximum number of passengers waiting at all stations to the number of stations is a measure of the average platform capacity required by stations in the network. Either measure can be used to compare the requirements of one system with another.

The primary measure of design efficiency is the life cycle cost per passenger trip, and this measure should be used for system-level comparisons of alternate AGT system deployments. However, evaluation of this high-level measure requires definition of all aspects of daily operation as well as specification of unit cost estimates.

Cost estimates are often treated parametrically because only the range of unit cost parameters can be estimated with confidence in many cases. In addition, it is often desirable to estimate relative cost impacts of certain design parameters without defining all aspects of the deployment. Therefore, lower level measures which relate to system costs should be considered when possible. Fleet size is a system parameter which can be legitimately considered a measure of system efficiency because its value is established as a result of performance analysis. It is a reasonable

surrogate for system cost because the cost of the vehicle fleet is often the largest element of system cost next to that of the guideway and stations. If systems with different sizes or types of vehicles are being compared, consideration of fleet cost estimates is often more revealing than consideration of fleet size alone. Vehicle operating and maintenance cost, a major component in total variable cost, varies directly with vehicle kilometers traveled. Thus, vehicle kilometers is another useful measure of system efficiency. If the deployments being compared have significant differences in network configuration or vehicle characteristics, large differences in the number of vehicle kilometers traveled may exist. To normalize the effects of these differences, system load factor (defined as passenger kilometers per vehicle capacity kilometer) can be considered as a measure of design efficiency. When considering these alternate lower level measures of system efficiency as more easily evaluated substitutes for system cost, care should be exercised so that other parameters, which may be important contributors to system cost, are not ignored entirely. For example, a variation in vehicle size may have a significant impact on station size and cost or on guideway unit cost.

When comparing alternative AGT systems deployed on similar networks in the same application area, the single most important measure of service effectiveness is passenger wait time. Several different values of wait time are of interest both during the design of the system and later during the comparison with alternative systems. The average wait time for passengers at the most congested station during the peak hour and the 95th percentile wait time (value below which 95 percent of all wait times fall) are most useful as design constraints in analyses to specify values of system parameters. System average wait time for the peak hour of each demand period and for the service day as a whole are useful measures for comparative purposes. The absolute maximum wait time that occurs during a simulation experiment applies to a singular event, and it is very sensitive to random variations in demand and vehicle motion. As a consequence, it is sometimes a misleading indicator of system performance. The 95th percentile wait time value, on the other hand, is based on a larger sample of individual trips and is therefore a more repeatable and useful measure. The

average time required for the remainder of the trip on the AGT system after the initial wait is an important measure. However, since average travel speed can be more easily related to the performance of other modes and to AGT systems deployed on alternate networks than travel time, travel speed is recommended as a measure of service effectiveness. Intermediate stops and transfers detract from travel speed, but their negative effect on ridership potential may go beyond their effect in increasing total trip time. Therefore, the average number of intermediate stops and the fraction of passengers who must transfer from one AGT vehicle to another are also recommended for use as measures of service effectiveness.

The probability of encountering an unacceptably long delay due to system failure is a very important system performance measure. The SOS software evaluates two measures of system availability. Passenger-based availability is calculated as the proportion of passengers who do not encounter failure induced delays greater than a threshold value (e.g., five minutes). Vehicle-based availability is defined as the ratio of failure free vehicle hours to total vehicle hours of operation. Throughout the System Operations Studies project passenger-based availability was consistently shown to vary in essentially the same way as vehicle-based availability, but the passenger-based value tends to have a greater range of variation for a given variation in system or network configuration.[1] Therefore, passenger-based availability is recommended as the primary measure of system dependability.

Table 5-1 provides a summary of the primary and alternative measures recommended for use in evaluating AGT systems using the SOS software. These measures are intended for use in comparing alternative AGT system configurations designed to serve the same general application area. Of course, less aggregate measures of system performance, which are also evaluated by the SOS software, will be used to determine the values of certain design parameters such as fleet size, cruise velocity, and station dwell time.

TABLE 5-1. SUMMARY OF SYSTEM-LEVEL MEASURES OF AGT SYSTEM PERFORMANCE

OBJECTIVE	PRIMARY MEASURE	ALTERNATIVE MEASURE
Design Feasibility	Maximum Link Utilization	Number of links operating above 70 percent of maximum theoretical capacity
	Maximum number of vehicles occupying a station	Maximum number of vehicles entering a station per sampling interval
	Maximum number of passengers waiting at a station	Ratio of maximum number of passengers waiting at all stations to number of stations
Design Efficiency	Life cycle cost per passenger trip	Fleet size or fleet cost Vehicle kilometers traveled System load factor
Service Effectiveness	System average wait time	Average wait time at the most congested station
		95th percentile wait time
	Average travel speed	Average number of intermediate stops
		Fraction of passengers who must transfer
	Passenger-based system availability	Vehicle-based system availability

6.0 INITIAL SYSTEM DEFINITION AND SCREENING

The analysis of AGT system alternatives can be approached as a three part process including initial system definition and screening, trade-off analysis, and sensitivity analysis. The purpose of this first phase of analysis is to initially define system deployments to be considered in later trade-off analyses. A deployment consists of a specific network configuration, a system technology, and a demand. Candidate network configurations are specified as described in Section 4.0. The definition includes specification of the number and location of stations, station type (on-line or off-line) and network connectivity (shuttle, loop, grid). During this phase of analysis, system technology is defined at two levels. First, system alternatives are defined for initial consideration in terms of vehicle class (based on ranges of vehicle capacity) and service policy. Nominal values of other system parameters, such as cruise velocity, minimum headway, vehicle capacity, and dwell time, are specified to more completely define each candidate system. Later in the analysis process, the sensitivity of system performance and costs to variations in these other parameters is investigated. The second level of system definition which is addressed in this phase of the analysis involves the specification of subsystem characteristics to support the system level analysis. The characteristics of vehicles (Appendix B), vehicle control (Appendix C), and stations (Appendix D), as well as estimates of unit cost (Appendix E) and reliability parameters (Appendix F) are established through subsystem analyses. Appendices B through F present the results of subsystem analyses performed during the System Operations Studies to define subsystem data required to support system-level modeling and evaluation. Demand for each combination of network configuration and system alternative is estimated as described in Section 3.0. Finally, the deployment alternatives are screened to identify a manageable number of candidate system deployments for more detailed trade-off and comparative analyses.

In this section of the Analysis Procedure, the primary system parameters which are suggested for use in defining alternative system deployments are identified, and a procedure for screening the deployments is presented.

6.1 PRIMARY SYSTEM DEFINITION PARAMETERS

The initial definition of system deployments is in terms of primary system parameters for each network configuration. These parameters, which define basic system concepts, include system class and service policy. In this section, the AGT system classification structure developed during the System Operations Studies is reviewed, the service policies modeled by the DESM are summarized, and general approaches toward defining alternate routing structures for scheduled service are suggested.

A classification structure for AGT systems was developed to serve as a guide in selecting a variety of system types for consideration in the System Operations Studies. The system classification was also useful in organizing vehicle data so that nominal values of vehicle characteristics could be established. The classification structure permits existing and proposed AGT systems to be easily and unambiguously classified into one of several distinct classes which emphasize major differences in level of service and general applicability to various urban environments.

Two system parameters (traveling unit capacity and maximum cruise velocity) were selected to define the classes. Traveling unit capacity is the nominal capacity of the minimum train consist. Since in some systems two or more vehicles are permanently coupled in trains, traveling unit capacity rather than vehicle capacity was selected as a classification parameter to more accurately reflect the service capabilities of systems. Vehicle velocity influences service level through its direct effect on travel time. Maximum speed capability also implies a range of applications for which a system may be suited. Maximum operating speed rather than cruise speed is used as a classification parameter because the former describes a system capability while the latter may refer to a network constraint or deployment option.

The various classes are defined in Table 6-1. Three major categories are identified on the basis of traveling unit capacity: Personal Rapid Transit (PRT), Group Rapid Transit (GRT), and Automated Rail Transit (ART). GRT is further partitioned into three distinct ranges of traveling unit

TABLE 6-1. GM TSC CLASSIFICATION STRUCTURE

Category	Class	Subclass	Service Type	Minimum Traveling Unit Capacity (Passengers)	Maximum Operating Speed (km/hr)	Characteristic Minimum Headway (s)	Example System
PRT	PRT	low speed	non-stop	3-6	13-54	3 or less	Cabinentaxi
		high speed	non-stop	3-6	55+	3 or less	CVS
GRT	SGRT	low speed	multiple-stop	7-24	13-54	3-15	Morgantown
		high speed	multiple-stop	7-24	55+	3-15	UMTA-AGRT
	IGRT	low speed	multiple-stop	25-69	13-54	15-60	Airtrans
		high speed	multiple-stop	25-69	55+	15-90	Unimobile Transporter
	LGRT		multiple-stop	70-109	13-54	50-109	SEA-TAC
ART	ART		multiple-stop	110+	55+	60+	WMATA

Legend

PRT - Personal Rapid Transit
GRT - Group Rapid Transit
SGRT - Small Vehicle GRT
IGRT - Intermediate Vehicle GRT
LGRT - Large Vehicle GRT
ART - Automated Rail Transit

capacity -- Small Vehicle GRT (SGRT), Intermediate Vehicle GRT (IGRT), and Large Vehicle GRT (LGRT). The resulting five classes are further divided as appropriate into eight subclasses on the basis of maximum operating velocity. The subclasses are uniquely defined in terms of the classification parameters in Table 6-1. The range of minimum headway which is characteristic of systems in each subclass is given in the table. An example of each system class -- either a system which has been deployed or one which is under active investigation -- is also given in the table.

In the initial system definition process, one or two representative systems from each applicable class are selected for consideration. Variations in vehicle capacity within each system class are considered later in a sensitivity analysis after more basic system parameters have been evaluated.

Service policy is another primary parameter used to define initial system deployments for analysis. The DESM supports the modeling of several demand responsive and scheduled service policies. The demand responsive service policies include single-party service, which is characteristic of Personal Rapid Transit concepts, and multiple-party service, which is often considered for Group Rapid Transit systems. In multiple-party demand responsive service each vehicle is routed along a minimum path from origin station to the ultimate destination station. Vehicles are permitted to divert to intermediate stations along the minimum path to pick up and discharge passengers. An alternative multiple-party demand responsive service policy does not permit vehicles to divert to intermediate stations unless a passenger on-board has that station as his destination. This tends to limit the number of intermediate stops that the passengers experience. A third alternative, multiple-party non-stop service based on the Morgantown Phase II service policy is scheduled for implementation into the DESM during 1980. Fixed routes for scheduled service can be generated by the DESM (Cycle Routes) or defined by the user. Cycle Routes are minimum path routes which provide no-transfer service between every station pair. The DESM also accepts user-defined routes which may require transfers. Both DESM-defined Cycle Routes and user-defined routes must be cyclic; i.e., begin and end at the same station. A third scheduled service alternative, termed open

routes, is scheduled for future implementation into the DESM. In this case routes do not begin and end at the same station. When a vehicle reaches the end of an open route, it is assigned to another route or to the same one according to a user-specified list of priorities. A mixed mode of operation, in which the open route strategy can be specified for some station pairs while one of the demand responsive strategies is specified for other station pairs, is also scheduled for implementation in the DESM in 1981.

Since routing structure impacts station-to-station trip time and trip time is a major parameter in demand estimation, the routing structure must be defined before the patronage analysis is completed. Several different approaches can be followed to define routes for a given system deployment. One approach is to use the Cycle Route routine of the DESM to automatically generate a set of routes. One disadvantage of this approach is that a large number of routes tend to be defined partially due to the fact that no transfers are permitted. Since the maximum number of routes is a parameter which affects the memory requirements of the DESM, the processor is usually compiled for a relatively small number of routes (e.g., 30). Use of the Cycle Route routine, therefore, may require a recompilation of the processor. One-way or open routes can be automatically generated using the AGT performance assessment model generated at the Applied Physics Laboratory of The Johns Hopkins University (APL/JHU).[22] The APL model generates a set of open routes based on a specific demand, the maximum number of intermediate stops per passenger trip on a given route, and the transfer policy (no transfers or limited transfers). The APL model also tends to generate a large number of routes even when the limited transfer option is selected. In addition, a modification to the DESM, which is planned but not yet implemented at the time of this writing, is required to permit the modeling of open routes.

The third suggested approach to defining routes is a manual one in which an analyst applies his knowledge of the demand and the application area to define a limited number of routes to serve all station pairs either with or without transfers. An initial estimate of station-to-station demand is useful to help identify high-demand station pairs which should be served as

directly as possible and to identify low-demand station pairs for which transfer service might be considered. To eliminate the influence of routing structure in this initial demand estimate, the use of the DESM with a demand responsive service policy to estimate direct station-to-station travel times for use in the demand estimation processor (FSM or other model) is recommended. Once an initial estimate of demand has been generated, it can be used to postulate alternative routing structures. One set of routes can be obtained by blanketing the network with a few different routes in which vehicles stop at all stations along the route. This will generally result in the fewest routes being proposed although they will tend to require the most intermediate stops and transfers. Using this all-stop routing structure as a basis, the level of service between selected station pairs can be improved by specifying additional express routes or alternate skip-stop routes. An heuristic approach, developed by Hadlock and Yuan,[78] can also be utilized to generate the minimum number of different routes subject to given level of service and cost criteria. Once alternative sets of routes have been defined, the patronage analysis is repeated for each alternative to reflect the differences in estimated station-to-station trip times on demand.

6.2 SCREENING OF INITIAL SYSTEM DEPLOYMENTS

With so many potentially feasible combinations of vehicle class, service policy, and network configuration, a deployment screening process is required to limit the number of deployments to be considered in subsequent detailed trade-off and sensitivity analyses. To evaluate these deployments fairly, a consistent method must be employed to specify a reasonable active fleet size for all of the deployments. The Input Processor of the DESM calculates the number of vehicles required to serve the demand subject to a maximum wait time (maximum route headway) constraint for scheduled service or an estimated achievable load factor specification for multiple-party demand responsive service. It is suggested that this capability of the DESM be utilized to specify system capacity. While the resulting system performance may not be totally acceptable, the relative performance of the deployment alternatives can be fairly compared because in each case reasonable system capacity has been specified according to a consistent process.

Since, in general, the deployments are not well defined at this stage of analysis, the screening process should be based on top-level, easily-evaluated measures which reflect system feasibility, efficiency, and effectiveness. As indicated in Section 5.0, feasibility relates to the ability of a deployment to serve the demand without producing unreasonable congestion delays. Average vehicle speed on guideway links is an overall measure of this ability which is calculated by the DESM. The ratio of this measure to the average cruise velocity specified for the guideway links is suggested as a normalized measure of overall system feasibility. Congestion on individual links should be considered, at least briefly, in this stage of the analysis to identify possible network modifications which might reduce vehicle congestion. An alternate measure of feasibility which can be obtained from DESM output is the proportion of passengers served whose excess travel time is less than a user-defined threshold value. Excess travel time is defined as the amount of time by which the actual travel time exceeds the nominal travel time. In scheduled service, nominal travel time includes the minimum time required for scheduled intermediate stops. However, time required for intermediate stops is not included in nominal travel time for demand responsive service. Therefore, excess travel time is not necessarily a measure of congestion on the guideway in demand responsive systems. The use of this alternate measure in the screening process should be avoided when scheduled service deployments are to be compared on a competitive basis with demand responsive deployments. In addition to one of the system feasibility measures mentioned above, the level of demand which is attracted by the system should also be considered in the screening process. Since the deployments being compared are designed to serve the same application area, the station-to-station demand for each deployment can be normalized by dividing it by the total zone-to-zone demand for the application area. This demand ratio is a relative measure of network coverage and level of service.

A fundamental measure of work performed by a transit system is passenger distance travelled. Thus, a fundamental measure of transit system efficiency is the ratio of passenger kilometers travelled to the maximum amount of work that could be performed by the system if vehicles were fully loaded at all times (i.e., the product of vehicle kilometers travelled and

vehicle capacity). This ratio, called vehicle load factor, is calculated by the DESM and is suggested for use as a normalized measure of system efficiency in the deployment screening process.

Important measures of system effectiveness include all the separate elements of trip time including initial wait time, travel time, and delays due to intermediate stops, transfers, and congestion. Average trip speed is a top-level measure which incorporates the effects of all these elements. While important information about a system design can be gained by considering the elements of trip time individually, the aggregate measure (average trip speed) provides a reasonable means to initially assess the potential effectiveness of deployment alternatives. In order to maintain consistency with respect to magnitude among the suggested measures, the ratio of average trip speed to average cruise velocity as specified in the input is suggested for use in the screening process.

In summary, it is suggested that the DESM be used in the process to screen the deployment alternatives by first calculating the required fleet size and then evaluating top-level measures of performance. The following four normalized measures can be used to rate the feasibility, efficiency, and effectiveness of deployment alternatives:

Ratio of average vehicle speed to average cruise velocity*
Ratio of station-to-station demand to total zone-to-zone demand
Average vehicle load factor
Ratio of average trip speed to average vehicle cruise velocity

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* An alternate measure, which can be used when scheduled systems are not being compared directly with demand responsive systems, is the proportion of passengers whose excess travel time exceeds a given threshhold value.

7.0 SYSTEM TRADE-OFF ANALYSIS

The purpose of the second phase of the system analysis is to evaluate major subsystem alternatives within each of the candidate system deployments. Specifically, the objectives of the trade-off analysis are to specify preferred alternatives for each deployment and to evaluate system performance, cost, and availability measures.

In this section the design parameters to be considered in the trade-off analysis are presented, and a procedure for using the SOS software to conduct the analysis is outlined.

7.1 DESIGN PARAMETER ALTERNATIVES

This phase of the system analysis deals primarily with the consideration of parameters which have the potential to relieve congestion and to improve level of service. As a result of the deployment screening analysis, certain network modifications may be indicated which might significantly reduce congestion in some area of the network. Network modification alternatives range from the addition of bypass links or additional lanes to the reversal of flow direction of some links in a single-lane network.

For systems which provide demand responsive service, several empty vehicle management alternatives can be evaluated using the DESM. As vehicles become empty, they are sent to storage locations or circulated on the guideway according to a set of options which can be specified in the input in order of highest priority. The following empty vehicle dispatch alternatives are modeled:

1. Local storage
2. Regional storage
3. Station storage according to anticipated need without considering current availability of empties
4. Station storage according to anticipated need while considering current availability of empties
5. Circuitous guideway route
6. Station with the most requests

In the local storage option, a vehicle is stored at the station at which it becomes empty until the vehicle is needed again to serve a passenger originating at that station. In the second alternative, a set of stations are identified as regional storage centers. Each station is assigned a regional storage center to which it sends empty vehicles. Each station is also assigned a regional storage center from which it retrieves empties as required to serve trip requests. Since the regional storage centers also serve as passenger stations, they must be selected with care to prevent the overloading of regional storage stations and the guideway links approaching them. The third and fourth alternatives require an analysis of the network demand pattern to determine the difference between the average number of vehicles which become empty and the average number of empties which are required at each station. Excess empty vehicles are sent to stations which have a deficit of empty vehicles. As an option, the Input Processor of the DESM automatically performs this analysis and calculates the required input parameters. In the third alternative, empty vehicles are sent to stations according to anticipated need without considering the current distribution of empty vehicles. In the fourth alternative, the current distribution of empty vehicles is considered in the disposition of empties. The fifth empty vehicle dispatch alternative requires that the user define a set of circuitous routes to which empty vehicles are dispatched to circulate on the guideway until they are needed to serve one or more passengers at one of the stations on the route. Use of this strategy can contribute to guideway congestion but it can also assure that empty vehicles are routed to low demand areas of the network where passengers may otherwise wait an excessive amount of time before an empty appears. When this alternative is evaluated, the effects of alternate routes should be considered. In the final alternative, empty vehicles are dispatched to the station in the network with the largest number of unanswered requests for empty vehicles. A request for an empty vehicle is generated when the simulation is unable to immediately locate a compatible vehicle which can be expected to serve a passenger trip within a specified period of time.

Along with the empty vehicle dispatch alternatives, the DESM models several empty vehicle retrieval alternatives. The list of where to look for

an empty vehicle, which can be specified in order of highest priority by the user, includes the following:

1. A non-circuitous vehicle about to arrive/bypass the station
2. A user input list of station link types which are to be searched for empty vehicles
3. The storage link of the station where the empty vehicle is needed
4. Regional storage
5. An empty vehicle circulating on the guideway on an empty vehicle route
6. Earliest available vehicle
7. Any expected arrival
8. Storage link of any station in the network

Several of these alternatives must be paired with the appropriate empty vehicle dispatch alternative. The sixth and seventh alternatives are combinations of other applicable alternatives. The last alternative expands the search for an empty vehicle to all stations in the network. The trade-off analysis for demand responsive systems should include an evaluation of these empty vehicle retrieval alternatives as well as an evaluation of empty vehicle dispatch alternatives.

Demand responsive service can often be improved by employing the vehicle reservation option. This option permits a passenger to reserve space on a vehicle scheduled to arrive at his origin station within a specified amount of time. The option is especially useful in improving service for passengers who originate downstream from high-demand stations.

One of the major design parameters to be specified in the design of an AGT system which provides scheduled service is the consist for each route. If several routes share segments of the guideway, the resultant headway may approach the minimum safe headway if single vehicles are used. However, if vehicles are operated in trains, the route headway can be increased, and congestion on guideway links which are shared by several routes can be reduced or eliminated. The penalty for longer route headways is usually longer average wait times on the route. However, if a congestion problem is

relieved, system average wait time may actually be reduced by the operation of trains rather than single vehicles on certain routes.

Demand stop is another option that should be investigated during the trade off analysis of scheduled system design alternatives. During demand stop operation, vehicles stop at stations only when necessary to serve specific demand requests (i.e., to board or deboard passengers). The demand stop service strategy was found to be generally ineffective when considered in the context of SLT systems with relatively high off-peak demand. In the deployments that were studied during the System Operations Studies[24] the elimination of unnecessary station stops usually did not reduce the round trip travel time on a route sufficiently to permit a significant reduction in active fleet size. Therefore, the number of vehicle kilometers traveled increased, resulting in increased energy costs. Service did not generally improve due to the tendency of vehicles to bunch on the route. However, conditions vary from one deployment to another, and demand stop or demand responsive service should be considered for periods of low demand.

7.2 TRADE-OFF ANALYSIS PROCEDURE

The active fleet size required to provide acceptable service is the primary dependent variable to be evaluated in the trade-off analysis of the design parameters described in the previous section. Once an adequate fleet size has been established for each different deployment configuration in each demand period, system performance and costs can be evaluated and used to judge the various alternatives. In this section the use of the SOS software to determine adequate fleet size and to evaluate measures of system performance and cost is described.

After parameters to be evaluated in the context of each candidate system deployment have been identified, the first step in their evaluation is to specify the input to the DESM required to describe the system alternatives. Much of the input has already been prepared as part of the demand estimation, network modeling, and deployment screening processes. However, for the sake of convenience all of these inputs are discussed at this time. The basic inputs required to run the DESM are contained in individual

members of partitioned data files. Two major types of files are involved: Input and Description (IANDD) and Structured (STRUC) data files. The first type are generated by the user as input to the Input Processor of the DESM. The second type of data file is generated by the DESM, and many of these files serve as inputs to the DESM Model Processor and Output Processor. The IANDD.DEMAND file defines the station-to-station demand in terms of the number of passengers traveling from each station to all other stations. The file also contains the trip size distributions. Members of this file can be generated directly by the FSM except for the trip size distribution data which must be added by the analyst. If a modal split model is used, some reformatting of the data by the analyst may be necessary. The trip list, which is described in Section 3.0 and serves as the demand input to the DESM Model Processor, is a member of the STRUC.DEMAND file. As indicated in Section 3.0, the trip list can be generated by the DESM Input Processor using a compound Poisson process, or it can be generated by an exogenous process. For the purpose of this trade-off analysis, it is suggested that the Deterministic Demand Preprocessor (DDP) be used to generate a non-random trip list for the reasons cited in Section 3.0. The IANDD.NETWORK file defines each link in the network in terms of entry node, exit node, length, and whether or not a station is located on the link. The STRUC.NETWORK file is generated by the Input Processor and includes minimum path and link travel time data in addition to network connectivity and station identification information. The IANDD.SYSTEM file contains system description data which tends to remain constant for a given deployment during the trade-off analysis. These data may include guideway link data, vehicle control data, service policy data, station configuration data, and simulation control data. The IANDD.RNTIM file contains other system description and simulation control data which is likely to be varied from one run to another. These data may include demand scaling information, vehicle fleet information, and information which is used to override data in the IANDD.SYSTEM file or to change the value of parameters at specific times during the simulation. The information in these files is structured for use by the Model Processor and is output by the Input Processor in two files, STRUC.SYSTEM and STRUC.RNTIM. A separate member of the IANDD.RNTIM file is developed by the user to define the output parameters and formats to be generated by the DESM Output Processor. Specific members of these files are

listed for illustrative purposes in the DESM User's Manual.[12] Other examples are stored on magnetic tape in the SOS data base. When generating input for the SOS software, it is more convenient to edit a copy of an existing member than to create a new member from scratch. The data base files can be used as a reference for this purpose in the first analysis. As a further aid in developing input data for the DESM, Appendix H is an input guide for the DESM. Most of the input variables which can be specified are identified in the guide along with suggested input formats. Some input parameters, which were not used to define system configurations in the System Operations Studies, are not included in the input guide. Some new variables introduced as a result of recent software modifications are also not included in the guide. Therefore, the DESM User's Manual[12] should be consulted before input data files are generated for the DESM.

Simulations start with the distribution of vehicles around the network when either the demand responsive or fixed route service mode is chosen. When demand responsive service is selected vehicle placement, at the entry to network stations, is accomplished either automatically by the DESM or specified by the user. When fixed route scheduled service is selected, the DESM will automatically compute the number of vehicles required on each user defined route, the headway, and the dispatch times from each station, based on the specific demand pattern. The user also has the option to specify either the number of vehicles or the headway requirements for each route in which case the DESM will automatically compute the associated headway or number of vehicles. Since the vehicles are initially empty and there are no passengers waiting at stations, the simulation should be allowed to progress until the system reaches a more normal state of operation before the aggregation of output statistics begins. The length of this system warm up period is under the control of the analyst who can specify the start and stop times for the processing of output statistics. An initial analysis should be conducted to determine an appropriate warm-up period so that the effect on performance measures of the transient associated with system start-up is eliminated. If the demand is constant during the system start-up period, a single simulation run can be used to select a reasonable start up time period. When the average vehicle load factor from one sampling interval to the next remains relatively constant, then it can be assumed that a relatively steady state operating point has been achieved.

When demand varies in either magnitude or distribution during the initial period of simulated operation, a comparison of several runs is required to establish an appropriate start-up period. In this case, an appropriate start-up period can be determined by comparing the results of simulations using different start-up periods and noting when the average value of system wait time reaches a relatively constant value.

Once an appropriate start-up period has been established for each deployment, the next task is to determine the fleet size required to provide an adequate level of service for each different system configuration. As indicated in Section 6.0, the DESM Input Processor can automatically estimate the fleet size required to serve a given demand represented by a specific input demand matrix. The analyst can control this estimate to some extent by specifying a target vehicle load factor for demand responsive systems or a maximum wait time (maximum route headway) for scheduled service systems. The fleet size estimated by the Input Processor is a useful starting point in this analysis, but it is usually necessary to test system performance by simulating system operation with several specific fleet size values in order to select the fleet size which most nearly satisfies performance goals at minimum system cost. For demand responsive systems this part of the analysis involves making several runs with different size fleets to test the performance of each alternative candidate system deployment and empty vehicle management strategy. Through a largely trial and error process the analyst determines the fleet size which produces the best balance between system costs and wait time (average and 95th percentile) and vehicle load factor goals.

It is usually unnecessary to calculate total system cost at this point in the analysis. The differences in system cost caused by different fleet sizes and station requirements can be determined and used in the analysis. Variations in fleet size cause variations in the costs of the vehicle fleet, maintenance facility, vehicle maintenance, and energy. Fleet size variations also cause variations in the number of passengers waiting for service which affect station costs.

The same type of trial and error simulation process is required to establish fleet and consist sizes for scheduled systems. However, in this case the process is guided by the use of an additional measure and a

relationship between flow capacity in passengers per second and average wait time. The average load of vehicles leaving individual stations is a useful measure generated by the DESM which indicates how closely capacity matches demand. For example, if the average load of vehicles leaving a particular station approaches 100 percent of capacity, system performance is likely to be very sensitive to random variations in demand or vehicle arrival rate. Therefore, an increase in fleet size for at least one of the routes serving the station is indicated. Other statistics generated by the DESM, such as maximum vehicle load and maximum wait time for each individual route, can be used to help identify a particular route for which a change in the number of trains or the train consist is required.

A linear relationship between flow capacity and average wait time was identified during the System Operations Studies.[1,24] The relationship can be used to analytically predict the effects on wait time of variations in design parameters such as train consist and number of trains per route as well as variations in sensitivity parameters such as vehicle capacity, cruise velocity, dwell time, and demand magnitude. The relationship can be established for AGT systems through the use of system simulation whenever the system wait time goal is expressed in terms of the average wait time at one critical station, and the platform queue at that station continues to grow throughout some portion of the demand period even though the demand remains essentially constant. The relationship between average wait time and passenger arrival and departure rates can be expressed in the following form:

$$(\overline{WT} - H/2) = \frac{T}{2}\left(1 - \frac{D}{A}\right) \qquad (7\text{-}1)$$

where

$\overline{WT}$ = Average passenger wait time at a congested station during the period

H = Average route headway

T = Any interval of time during which the platform queue at the congested station is increasing

D = Passenger dispatch rate at the station

A = Passenger arrival rate at the station

The difference between average wait time and one-half the headway is called the average queue transit time. The passenger arrival rate, A, is known from the demand matrix, but the passenger dispatch rate cannot be

known *a priori*. In general, the dispatch rate, D, is some fraction of the system flow capacity because vehicles are already partially loaded when they arrive at stations. Flow capacity, C, is the theoretical maximum flow rate (passengers per second) that can be accommodated by the system, and it is given by the ratio of traveling unit capacity to route headway. Traveling unit capacity is the product of vehicle capacity and train consist. If B is the fraction of total flow capacity available at the station (i.e., the arriving vehicles are 100(1- B) percent full of non-deboarding passengers), then D = BC; and the average queue transit time expression becomes:

$$(\overline{WT} - H/2) = \frac{T}{2} - \frac{(BT)}{(2A)}C \tag{7-2}$$

The determination of B, or equivalently, of the constant $\frac{BT}{2A}$ requires the use of simulation to establish how vehicles become loaded when the queues begin to build in stations. In general the value is different for each station in the network and for each time period for which the relative station-to-station demands are different. Thus, in order to be useful the relationship must be established separately for a congested station on each route.

Figure 7-1 is an example of the straight line relationship between average queue transit time and flow capacity for an SLT system analyzed during the System Operations Studies. The data points represent a.m. peak hour simulation results for one station and p.m. peak hour results for another station in a single-lane loop deployment. Once calibrated using simulation data, plots of this nature can be used to establish appropriate fleet sizes and train consists for each route. When flow capacity is specified so that the average queue transit time is greater than zero, the platform queue tends to continue growing throughout the period (i.e., the platform queue is unstable). During the System Operations Studies it was found that the performance of systems with unstable platform queues is very sensitive to even small, random variations in demand or vehicle arrivals.[24] It was also demonstrated that when system capacity is specified so that platform queues are stable, system performance is much less sensitive to variations in demand.[25] Therefore, it is recommended that the flow capacity which causes the average queue transit time to

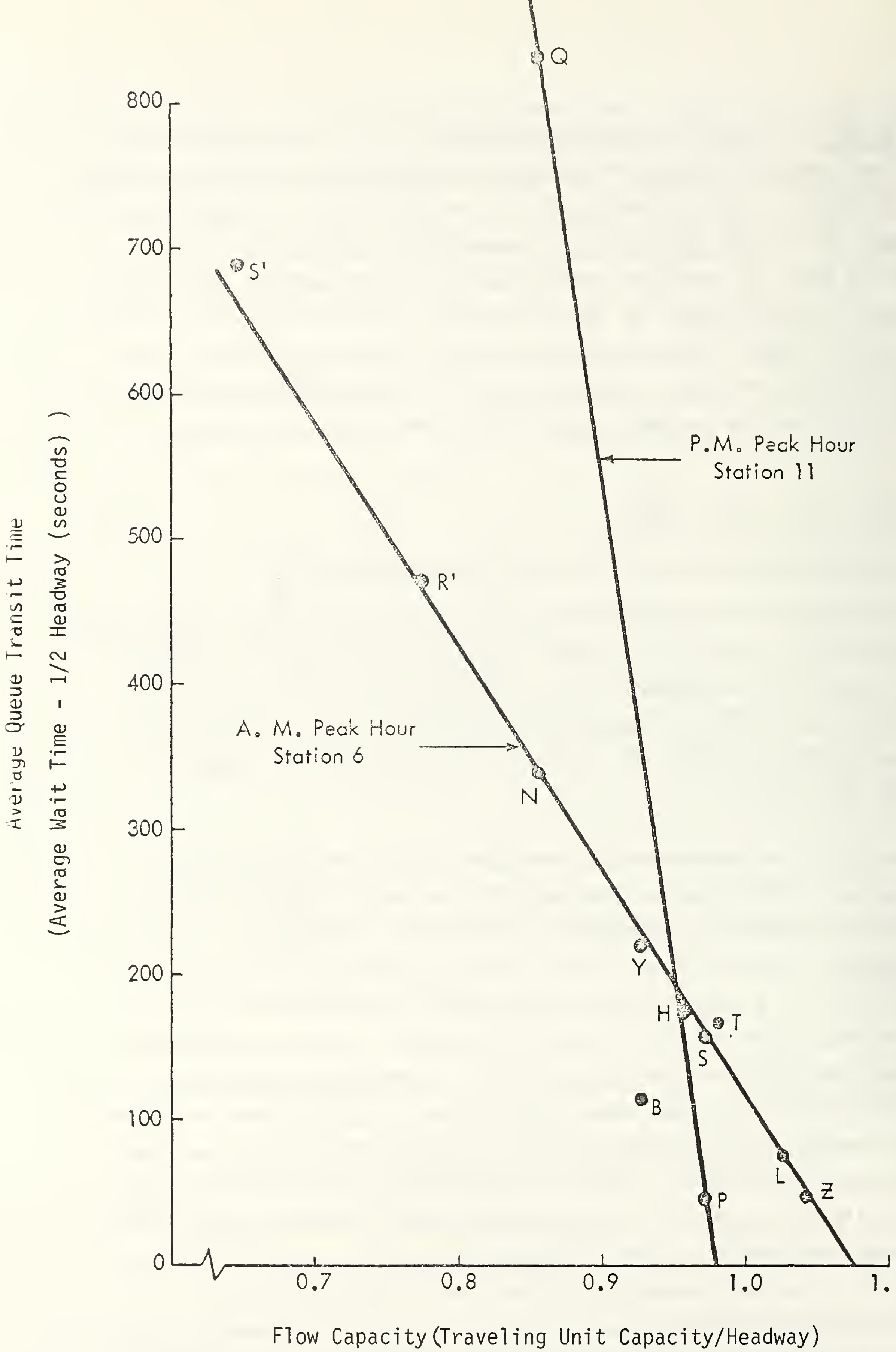

FIGURE 7-1. AVERAGE QUEUE TRANSIT TIME VERSUS FLOW CAPACITY FOR AN SLT SYSTEM

approach zero be selected as the design point for scheduled service systems. To determine this point, the simulation should be run for several relatively low values of flow capacity (high values of average queue transit time) to establish the queue transit time-flow capacity line for each route. Then each line can be extrapolated to estimate the value of flow capacity which corresponds to zero queue transit time for each route. In some cases it may be necessary to specify an even larger value of flow capacity to satisfy system wait time goals.

Once the required value of flow capacity has been estimated, alternative combinations of route headways and train consists can be evaluated for given values of vehicle capacity, link velocity, and dwell time. The queue transit time-flow capacity line can later be used to evaluate the sensitivity of system performance to variations in these parameters (vehicle capacity, velocity, and dwell time). In addition, since the passenger arrival rate, A, appears in Equation 7-2, the flow capacity can be scaled by the ratio of the original demand magnitude to a new demand magnitude to predict the effect on average wait time of a change in demand level.

In order to fully evaluate the various system alternatives, fleet size and operating characteristics must be determined for off-peak as well as peak period operation. The full range of demand responsive and scheduled service policies including demand stop should be considered. While the requirements of peak period operation define capital costs to a great extent, off-peak period operation contributes significantly to operations and maintenance costs. Therefore, the evaluation of off-peak service is an important part of the overall trade-off analysis.

Alternative system configurations are often compared on the basis of the demand attracted by the deployment, the total system cost, and the cost per passenger. All of these measures are strongly influenced by the magnitude of demand which the system is designed to serve. The original patronage estimates, described in Section 3.0, are determined using preliminary estimates of system performance. At this point in the analysis, after the fleet size for each alternative deployment has been determined, an improved estimate of system performance is available for use in a demand analysis.

If the current estimate of performance is substantially different from the preliminary one used in the original demand analysis, demand should be re-evaluated. To complete the iteration, system performance and fleet size should be re-evaluated based on the latest demand estimates for each deployment alternative.

The next step in the system trade-off process is to estimate system costs. The System Cost Model (SCM) can be used to estimate capital, operating, maintenance, and life cycle costs for each alternative system deployment. Several environmental measures are also calculated by the SCM -- namely, energy consumption, pollution, and land use requirements. The SCM is an interpretive program that uses an input equation set and input cost data to determine life cycle cost measures. The SCM input is structured to facilitate the cost analysis of several similar system deployments. The data on which the cost equations operate are contained in three separate data files. Some of the input data remains relatively unchanged as various systems are evaluated. These data are contained in the common file (IANDD.SCMCOM), and they include unit costs for building construction (e.g., station costs per square meter of area), unit energy requirements for non-propulsive purposes (e.g., annual energy per square meter required for air conditioning buildings), and general cost factors (e.g., percent of total vehicle costs required to stock the spare parts inventory). Other input data tend to vary with major system class but to remain essentially fixed for a given system class. These data, which are stored in the system file (IANDD.SCMSYS), include such items as vehicle and guideway unit costs. The third type of input required by the SCM is of a site specific nature. These data tend to vary with each different configuration of a given system deployment, and they are stored in a deployment file (IANDD.SCMDPLY).

A description of the partitioning of system deployments into cost categories and unit cost input suggestions are presented in Appendix E. Detailed information on the use of the SCM is presented in the User's Manual.[15] The detailed system operations data required for each SCM run is determined by the analyst and based to a large extent on DESM output data. Some of the information, such as vehicle operating hours, is

determined from short-term simulation of the system. Other information, such as vehicle energy requirements and station building area, is computed by the analyst based on simulation results.

During the system trade-off studies, each system deployment is simulated for an interval of time during each major demand period such as a peak hour or an off-peak hour. For the purpose of estimating operating and maintenance costs, it is assumed that these relatively short-term results apply for the entire demand period. The results for each major demand period are then combined to estimate daily values based on the length of the service day. Once statistics for daily operation have been generated, they are expanded to annual values based on the assumed number of operating days per year for systems deployed in each application area.

Availability is the remaining dimension of a system deployment which should be evaluated to fully characterize it. However, the process of evaluating system availability is a rather involved and lengthy one. As outlined in Appendix F and illustrated in Appendix G, the process involves generating subsystem reliability data, estimating the consequences of failure through numerous DESM runs, and finally, evaluating system availability using the System Availability Model (SAM). The process requires a considerable amount of sound analyst judgment to estimate failure rate data, to select representative failures for evaluation, and to define reasonable failure recovery responses and response times. For these reasons it is recommended that the evaluation of system availablity be limited to a few superior system configurations. It is suggested that systems be selected on the basis of a few important measures such as life cycle cost per passenger, system average wait time and travel time, and 95th percentile wait time.

After completing the availability analysis, the selected set of system configurations can be evaluated on the basis of system availability to further limit the number of different system deployments to be considered in the next phase of analysis -- sensitivity analysis.

8.0 SENSITIVITY ANALYSIS

The trade-off analysis discussed in Section 7.0 establishes the baseline design parameters for an AGT system deployment. In so doing a specific network configuration would be developed, a service policy determined, and fleet size and vehicle training requirements established. Specific vehicle storage and retrieval algorithms would be chosen. Baseline parameters for vehicle capacity, cruise velocity, station dwell time, and headways on routes would also be selected. The baseline design parameters are thus chosen based on their interrelated effects on system performance and cost.

The purpose of the sensitivity analysis is to evaluate the effects on system performance and cost of variations in some of the design parameters whose baseline values were established during the trade-off analysis. To help structure this portion of the analysis, three categories of sensitivity parameters have been defined. The first group, primary sensitivity parameters, includes parameters to which system performance and costs are expected to be most sensitive. The second group includes parameters which are expected to have a less direct impact on system performance. The third group includes other system parameters which can be investigated using the DESM but which may be limited in their applicability. In general, the procedure for conducting the sensitivity analysis is to consider the effects on system design, performance, and costs of a variation in one parameter at a time. With the values of all other system design parameters held constant, the fleet size required to satisfy performance goals for each alternative value of the sensitivity parameter under investigation is determined using the DESM as described in Section 7.2. The life-cycle costs of the resulting systems are then evaluated using the SCM.

This section identifies the sensitivity parameters in each category and describes variations which should be evaluated.

8.1 PRIMARY SENSITIVITY PARAMETERS

The performance and costs of AGT systems are expected to be most sensitive to variations in the parameters of this first category. Primary sensitivity parameters include the following:

Vehicle Capacity
Cruise Velocity
Dwell Time
Minimum Link Headway
Demand
Unit Costs
Subsystem Reliability

Major variations in vehicle capacity are evaluated by comparing the performance and costs of system deployments which are based on different system classes. In the sensitivity analysis, small variations in system capacity (e.g., $\pm$ 20 percent) are evaluated.

Cruise velocity is normally constrained to a narrow range of variation by the travel time requirements on one hand and by propulsion power limitations and guideway curve constraints on the other. However, there are generally two incentives for altering the cruise velocity. First, if the velocity can be increased to the extent that fewer vehicles are capable of serving the same demand, then the capital and operating costs associated with the size of the AGT fleet can be reduced. However, vehicle energy consumption is likely to increase even if a reduction in the fleet size is possible. On the other hand, if performance goals can be satisfied by operating the same fleet at a reduced velocity, propulsion energy can be saved. In this case, however, a possible increase in the number of passengers waiting at stations may require larger, more expensive stations. These sensitivities to changes in the cruise velocity can be investigated using both the DESM and the SCM.

A single value of dwell time or a function to automatically calculate it is often assumed in the trade-off analysis. Since dwell time is somewhat of a random variable and since it has a significant effect on vehicle productivity, a parametric evaluation of dwell time variations on system performance should be conducted. If performance deteriorates beyond acceptable limits as dwell time is increased to a maximum expected value, then fleet size and system costs should be re-evaluated to reduce system sensitivity to variations in dwell time.

The queue transit time flow capacity graph which, as described in Section 7.0 is developed using the DESM, can be an aid when accomplishing the sensitivity analysis. In the case of scheduled service systems, the queue transit time-flow capacity graph can be used to predict the effect on average wait time of a variation in vehicle capacity, cruise velocity, or dwell time. For example, suppose Point H in Figure 7-1 represents the a.m. peak hour design point of an SLT system with 100 passenger vehicles. If the same number of 90-passenger vehicles were to be specified, Figure 7-1 can be used to estimate the effect on wait time. The reduction in vehicle capacity would reduce the flow capacity (traveling unit capacity/headway) by the ratio of vehicle capacities (90/100). In this example then, flow capacity would be reduced from .96 to .86. According to the relationship plotted in Figure 7-1, the queue transit time would be increased from 175 to 325s. Since the average route headway is 104s (100 pass per veh/.96), the average wait time increases from 227s to 377s. This 66-percent increase in average wait time for a 10 percent reduction in flow capacity indicates a very strong sensitivity of performance to variations in vehicle capacity. In order to maintain approximately the same average wait time, the flow capacity would have to be maintained at about .96 by reducing the average route headway. This could be accomplished either by increasing the number of vehicles on the route or by increasing the cruise velocity.

The degree to which the performance of an AGT system deployed on a grid network is affected by merge delays depends on the value of minimum link headway that is specified. The sensitivity of system performance to variations in headway should be evaluated to determine if a minimum headway requirement should be specified.

Demand projections for a public transit system are uncertain at best -- especially during the early planning stages. The effects on system performance of both random variations in demand and increased demand magnitude should be investigated. The Input Processor of the DESM can be used to generate random trip lists according to a compound Poisson process. A number of random trip lists generated using different random number seeds should be used to test the sensitivity of system performance. Both the DESM and the Deterministic Demand Preprocessor (DDP) accept scale factors as input to alter the magnitude of demand represented by the demand matrices.

Design sensitivity as well as performance sensitivity to changes in demand magnitude should be evaluated; i.e., in addition to the performance sensitivity described above, the increased fleet size required to adequately serve an increased level of demand and the associated increases in system cost should be determined to establish the relationship between demand magnitude and costs for each system.

Because of the variability and uncertainty that is usually associated with unit cost estimates and the importance of system cost as an evaluation measure, the effects on total system cost of variations in the values of major unit costs, such as those for guideway construction, vehicles, wages, and energy, should be evaluated. The sensitivity of system costs to variations in unit cost estimates can be evaluated by making repeated runs of the System Cost Model.

Similarly, the sensitivity of system availability to variations in subsystem reliability should be investigated by making repeated runs of the System Availability Model.

8.2 SECONDARY SENSITIVITY PARAMETERS

The second group of sensitivity parameters are expected to impact system performance and costs to a somewhat lesser extent than the primary sensitivity parameters. Included among the secondary sensitivity parameters are the following variables:

Vehicle Spacing Algorithm
Number of Seats per Vehicle
Standard Deviation of Vehicle Velocity

A number of alternative vehicle spacing algorithms are available in the DESM to help keep vehicles equally spaced on each route. Systems in which vehicles on a route are likely to bunch up due to merge delays, dwell time variations, or cruise velocity variations are likely to be sensitive to variations in the spacing algorithm. The effects of variation in two independent aspects of vehicle spacing should be investigated. The first aspect involves the extra dwell time or slack time used by the DESM Input Processor to determine route headway. When slack time is incorporated in the schedules, vehicles are delayed at stations during uncongested operation

until scheduled dispatch time, thus decreasing system capacity. However, the slack time allows vehicles to catch up to schedule through a series of undelayed dispatches following a delay due to congestion or a failure. Since slack time produces both an advantage (vehicles can catch up to schedule) and a disadvantage (capacity is reduced), it may be possible to improve overall system performance by varying the input value of slack time. The sensitivity of system performance to variations in this parameter should be investigated. The second aspect of vehicle spacing alternatives which should be investigated is the spacing algorithm itself. Two dispatch algorithms, which effectively debunch vehicles on a route, have recently been implemented in the DESM. Under the operation of the fixed separation dispatch algorithm, vehicles are scheduled for dispatch from stations one route headway time later than the actual previous dispatch on the route. This algorithm tends to limit capacity since any vehicle delay eventually causes all the vehicles on the route to be delayed. However, the algorithm maintains an almost constant separation among the vehicles on the route, and it effects a rapid debunching when necessary following congestion or a failure. The second dispatch algorithm, called midpoint separation dispatch, accomplishes an orderly debunching of vehicles while maintaining more system capacity than the fixed separation algorithm. Under the operation of the midpoint separation dispatch algorithm, vehicles are scheduled for dispatch midway between the actual departure time of the previous vehicle on the route and the current time plus one route headway time. An evaluation of these alternative algorithms should be conducted in conjunction with the consideration of the effects of a non-zero standard deviation of velocity and variations in dwell time parameters.

A design goal is sometimes specified which limits the maximum proportion of peak hour passengers who are not provided a seat (i.e., standees). To help assess the implications of these specifications, the sensitivity of system costs, energy consumption, and percent standing to variations in the number of seats per vehicle should be established. The analysis of AGT vehicle characteristics presented in Appendix B indicates the manner in which vehicle length and vehicle mass vary with seating capacity. For a given nominal capacity, the provision of more seats generally results in increased vehicle length and mass. These changes may result in increased station costs (longer platforms) and increased energy consumption. If

propulsive power is not increased to compensate for increased vehicle mass, vehicle performance may be degraded resulting in a reduction in cruise velocity. The system-level impacts of these variations should be evaluated if seating capacity (relative to nominal capacity) is an issue. Once vehicle performance has been defined, the DESM can be used to evaluate the fleet size required to provide adequate service. The SCM can then be used to evaluate system costs.

8.3 OTHER SENSITIVITY PARAMETERS

The third category of sensitivity parameters includes variables which are somewhat specialized in that most of them should be considered only in more complex deployments on grid networks. For the most part they represent alternative control approaches which may be considered to help relieve network congestion. The parameters in this category include the following:

Longitudinal Control and Dispatch Policies
Merge Policies
Vehicle Entrainment
Path Selection Approaches
Platform Configuration Alternatives

The longitudinal control and dispatch policies identified in Table 8-1 are modeled by the DESM. Synchronous and quasi-synchronous control refer to point follower while asynchronous refers to vehicle follower control.

TABLE 8-1. LONGITUDINAL CONTROL AND DISPATCH POLICY ALTERNATIVES

Longitudinal Control Strategy	Dispatch Policy		
	Deterministic	Quasi-Deterministic	Non-Deterministic
Synchronous	X		
Quasi-Synchronous	X	X	X
Asynchronous		X	X

Deterministic dispatch means that all merges are planned before the vehicle is launched from the station. In quasi-deterministic dispatch, a launch window is determined that attempts to minimize congestion at network merges. This window is achieved by delaying vehicle launch until such time that the number of vehicles scheduled to merge at all merges on the vehicle

path at the scheduled time of vehicle passage is below a user input threshold value. Non-deterministic dispatch requires no pre-planning of merge conflict resolution and results in no delay prior to launch of the vehicle from its current station.

Three alternative merge policies are modeled by the DESM:

1. FIFO -- The first in-first out merge policy permits the earliest arriving vehicle to enter the merge output first.
2. Heuristic FIFO -- In this merge policy vehicles entering the merge assume velocity changes based upon the density of traffic on each link approaching the merge. The velocity changes are defined by a user input table which can be developed from data generated by the Detailed Operational Control Model (DOCM).
3. Priority -- In this merge policy, vehicles on one link are merged ahead of vehicles on the other link.

In addition, priority merging can be defined on the basis of vehicle characteristics for off-line station merges. For these merges, priority can be given to either loaded or empty vehicles and to vehicles either exiting or bypassing the station.

The DESM also provides the ability to temporarily entrain and detrain vehicles operating in the demand responsive service mode. Dynamic (guideway) entrainment of vehicles can be performed on the downstream link of merges provided vehicles are sufficiently close. Static (station) entrainment occurs in the output areas of stations provided vehicles with a common destination become available for launch within a user input time limit. Detrainment is provided at guideway link diverges for dynamic entrainment and prior to dock entry in the case of static entrainment. These longitudinal control, merge policy, and entrainment alternatives were thoroughly evaluated for one GRT deployment during the System Operations Studies.[19] However, further analysis of these alternatives may be required for specific system deployments.

Path selection can be performed by the DESM on either an a priori or real-time basis. In a priori path selection, the entire route of the

vehicle to its next station is determined prior to launch from its current station. Real-time path selection involves the assignment of an initial path to the vehicle prior to launch and the re-evaluation of the path in real time as the vehicle traverses the guideway. Alternate paths in either mode can be selected according to the following criteria:

1. Link nominal travel time
2. Link length (distance)
3. Link utilization (occupancy/capacity)
4. Weighted combination of 1 and 3.

It is generally sufficient to consider only the _a priori_ path selection based on nominal travel time.* However, in some analyses involving complex grid networks, other path selection alternatives should be considered.

The DESM also permits a great deal of flexibility in defining station configurations. The effects of parallel platform lanes rather than one serial lane should be considered for stations which require high vehicle throughput. If limited station capacity results in vehicles not being able to enter stations, input and output queues should also be considered as station design alternatives. System simulation by the DESM can be used to assess the network effects of station design. The detailed operation of individual stations can be investigated using the Detailed Station Model (DSM). Vehicle arrival lists generated directly by the DESM can be used as input to drive the DSM.

8.4 APPLICATION OF SENSITIVITY DATA

The sensitivity data should be applied to the system deployments under investigation to define more nearly optimum configurations. In addition, the data should be organized to serve as guidelines for future design modifications as demand estimates and other design specifications change.

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* After a guideway link failure, the minimum paths are automatically recomputed with a large travel time penalty placed on the failed link. An alternate path around the failure is thus defined when possible.

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APPENDIX A

NETWORK MODEL EXAMPLES

In this appendix the network modeling requirements and guidelines presented in Section 4.0 of this report are illustrated through their application to several examples. With one exception, the examples were modeled and analyzed during the System Operations Studies. The networks include a shuttle, a single lane loop, a dual lane loop, and a line-haul grid. The final example, which was not analyzed during the System Operations Studies, is a bypass shuttle network.

The model of a dual lane shuttle network illustrates the use of several modeling techniques to satisfy DESM requirements. The basic network configuration is illustrated in Figure A-1. Figure A-2 illustrates an initial, unsatisfactory attempt to model the shuttle network. Vehicles travel in a figure-8 pattern on this network observing the unidirectional motion requirement. Nodes 4 and 5 are station entry and exit nodes, respectively. Since these nodes cannot serve as merge or diverge nodes, extra nodes (3 and 6) and links [(3) and (5)] were added to the network model. Instead of operating on separate guideway facilities, this network model requires vehicles to share the same guideway facilities. However, since the average time separation between vehicles operating on the two shuttles is on the order of 388 s, no merge conflicts are artificially induced by modeling the network in this manner. To further reduce the possibility of conflict, the minimum headway on links (3) and (5) was specified as one second. Two traveling units were assigned to the single route linking the three stations. The route forms a figure-8 pattern which passes through Station 2 twice during each cycle. This condition violates the first network definition guideline listed in Table 4-2. Passengers who originate at Station 2 use Route 1 (the only route) to reach destinations at Stations 1 and 3. Since the route number is the only vehicle attribute which is used by the DESM to determine the destination compatibility of vehicles and passengers, there is no way to prevent passengers from traveling from Station 2 to Station 1 via Station 3. For this reason, the figure-8 configuration is not a reasonable model of the dual-lane shuttle network.

FIGURE A-1. DUAL LANE SHUTTLE NETWORK CONFIGURATION

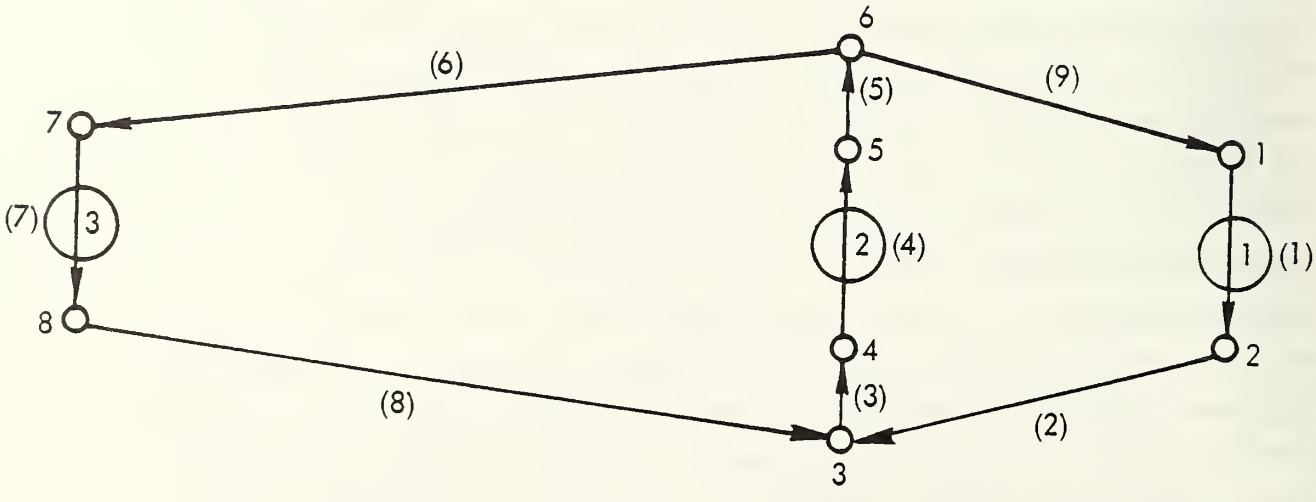


FIGURE A-2. FIGURE-8 MODEL OF SHUTTLE NETWORK

A better model of the shuttle network is illustrated in Figure A-3. The shuttle network is modeled as a simple loop, and the center station has been split into two stations. This network configuration allows both vehicle flow and passenger flow to be modeled accurately. However, it requires that the demand matrices be modified so that the demand to and from the original center station is divided appropriately between the new Stations 2 and 4. The new matrices can be derived from the original ones using the rule presented in Figure A-4.

In the event of a failure that causes a vehicle stoppage on one of the shuttle lanes of the reference network, vehicles can continue to operate unimpeded on the other shuttle. To model this characteristic of the dual-lane shuttle using a single-lane loop network model, failures must be constrained to stations where two platform lanes are assumed. Under normal operating conditions vehicles use the first platform lane at each station. To model a vehicle stoppage, one vehicle or train is immobilized in the platform docking lane. If the failure continues until the other vehicle or train arrives at the failure location, then that train is automatically assigned to the other platform docking lane. The operating vehicle can thus pass the failed vehicle and continue to provide service as if it had exclusive use of the loop.

Figure A-5 depicts a simple single-lane loop network configuration. The model of this network configuration, illustrated in Figure A-6, is straightforward. Each station is represented by an entry node and an exit node. The network model illustrated in Figure A-6 contains the minimum number of nodes and links required to represent the network. A larger number of nodes and links could have been used to more accurately represent the shape of the network. The use of a larger number of nodes to define the network is particularly important when the Network Build Module is used to estimate guideway length because the length is calculated as the straight-line distance between nodes. Once link lengths have been accurately determined, however, it is advisable to edit the network file to eliminate nodes and links that are otherwise unnecessary. The efficiency of the simulation is improved by the elimination of unnecessary nodes and links from the network model.

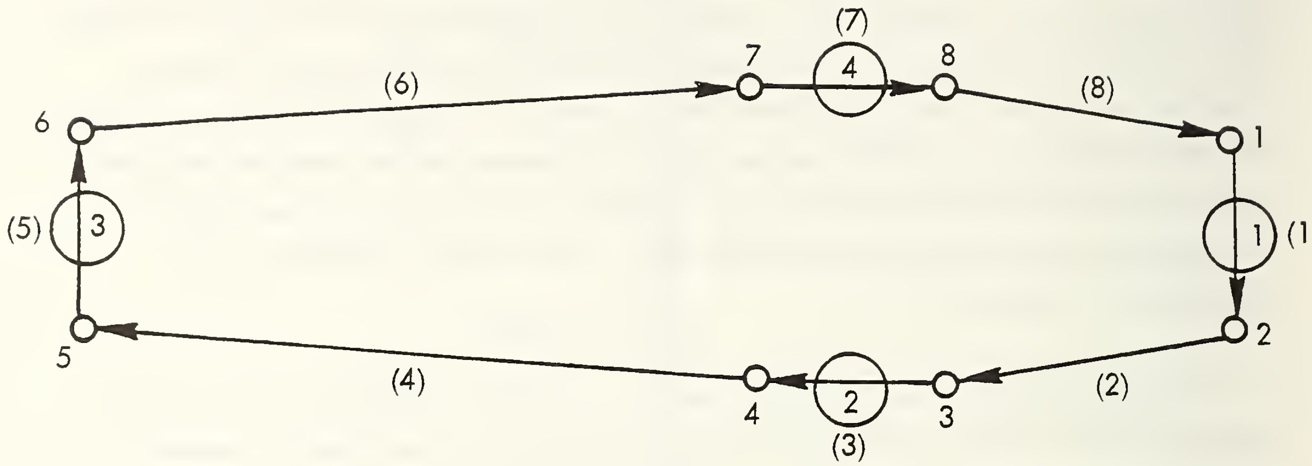


FIGURE A-3. LOOP MODEL OF SHUTTLE NETWORK

O \ D	1	2	3
1	O	d_{12}	d_{13}
2	d_{21}	O	d_{23}
3	d_{31}	d_{32}	O

Original Demand Matrix for Three-Station Shuttle Deployment

O \ D	1	2	3	4
1	O	d_{12}	d_{13}	O
2	O	O	d_{23}	O
3	d_{31}	O	O	d_{32}
4	d_{21}	O	O	O

New Demand Matrix for Four-Station Loop Model of the Shuttle Deployment

FIGURE A-4. DEMAND MATRIX EXPANSION RULE FOR THE LOOP MODEL OF A SHUTTLE NETWORK

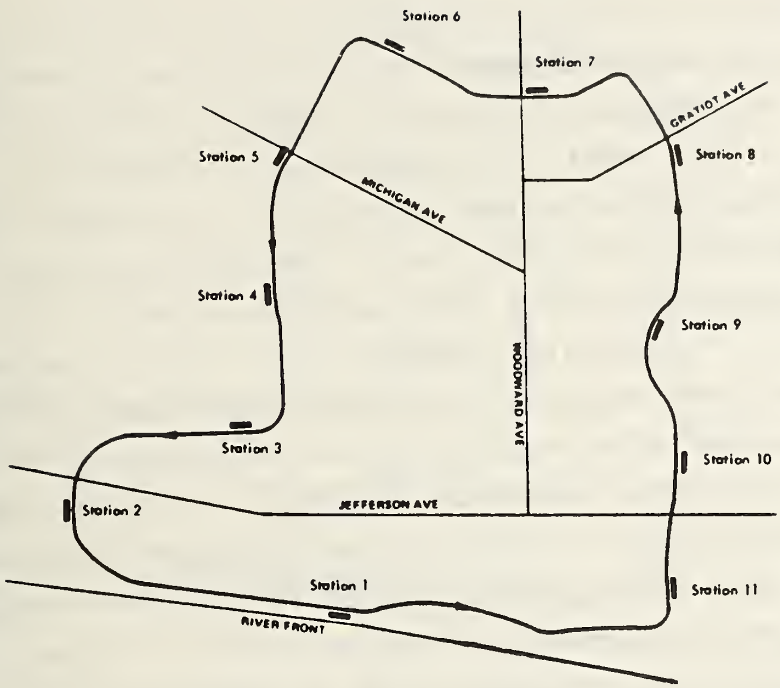


FIGURE A-5. SINGLE-LANE LOOP NETWORK CONFIGURATION

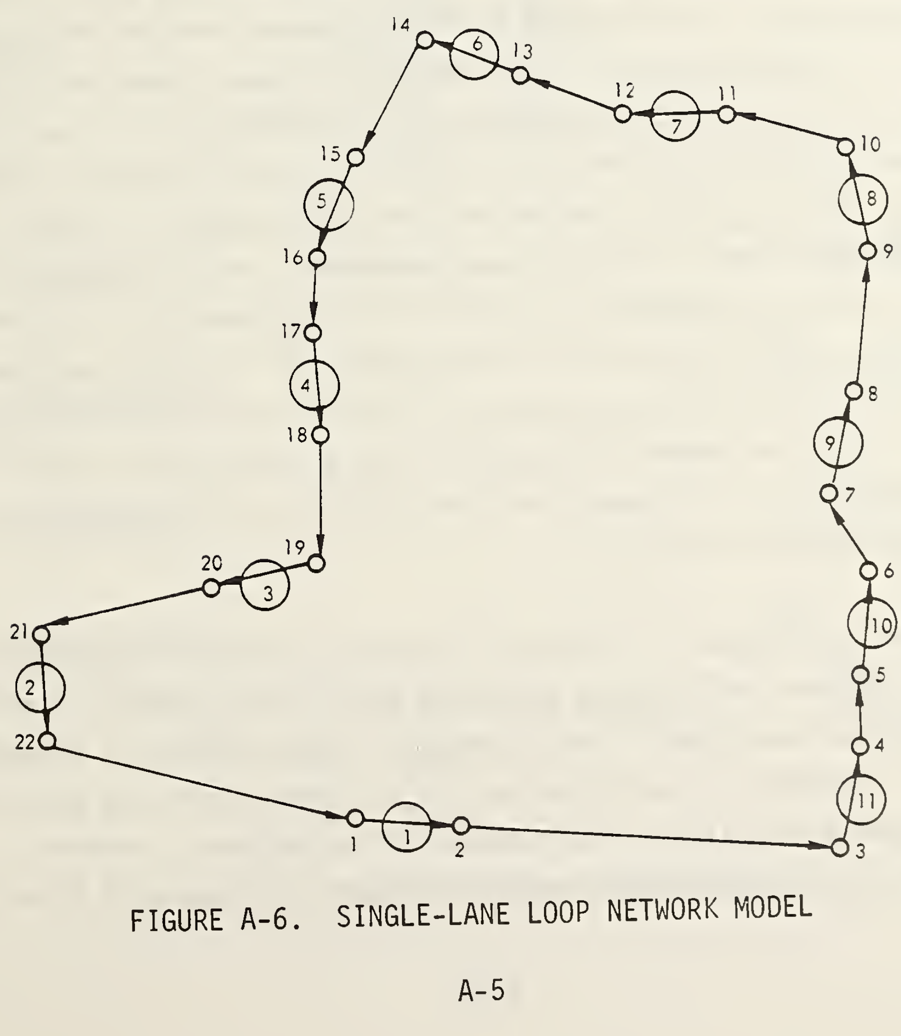


FIGURE A-6. SINGLE-LANE LOOP NETWORK MODEL

A dual-lane loop network configuration is illustrated in Figure A-7, and a sketch of a network model which represents this configuration is presented in Figure A-8. While the reference configuration appears to consist of two independent loops, the network model is fully-connected to satisfy the requirements of the minimum path algorithm. Although it is not shown in the sketch, the reference network probably has some limited interconnection between the loops to permit the use of a single maintenance and vehicle-storage facility. The network is modeled so that vehicles on both loops share the guideway links immediately upstream and downstream from the common stations. During simulation analyses, the minimum headway on these links was specified as one second to minimize the effects of possible merge conflicts which, of course, would not occur in an actual system. Stations were modeled as having two platform docking lanes so that vehicles traveling in opposite directions can simultaneously occupy the stations. In the analyses performed using this network model during the System Operations Studies, the probability that link travel time would be altered due to merge conflict maneuvers was very low because the route headways were long (158 s for each directional loop) compared to the one-second minimum headway assumed for the common links. If average route headways were much shorter and the possibility of noticeable delays due to merge conflicts were greater, then the use of guideway links by more than one route could be eliminated by splitting each station into two (directional) stations. The network model would then consist of two independent loops. Limited connectivity would be necessary to satisfy the requirements of the minimum path algorithm. This would be an accurate model of the dual-lane loop network, but it has the disadvantages that station statistics would be reported for twice the number of stations that actually exist in the reference network, and the demand matrices would have to be modified to represent the expanded network.

Figure A-9 illustrates an area-wide line-haul network configuration consisting of 28 on-line stations served by dual-lane guideway. A model of this network which was used in the System Operations Studies is presented in Figure A-10. The model illustrates the use of several modeling techniques to satisfy network definition requirements and guidelines. The most striking differences between the networks depicted in Figures A-9 and A-10

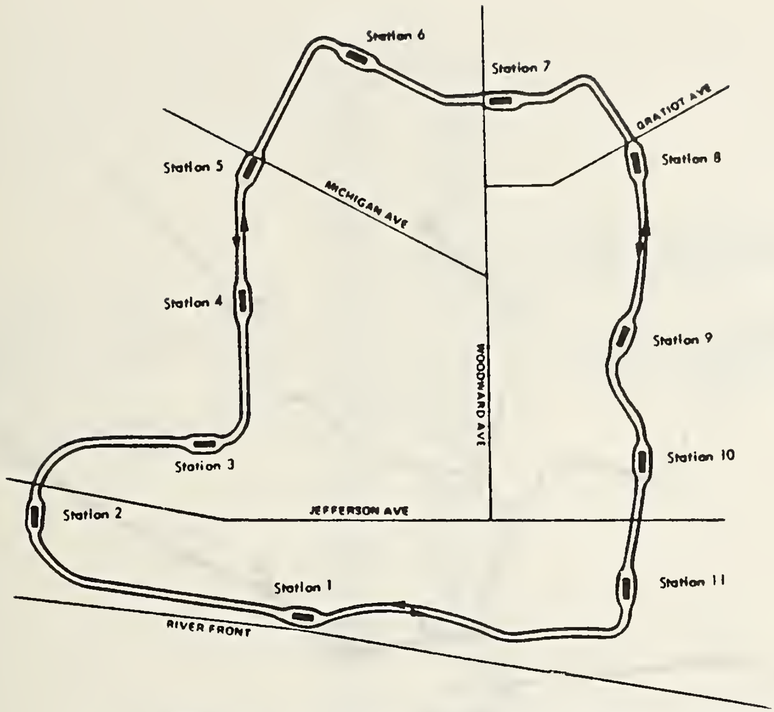


FIGURE A-7. DUAL-LANE LOOP NETWORK CONFIGURATION

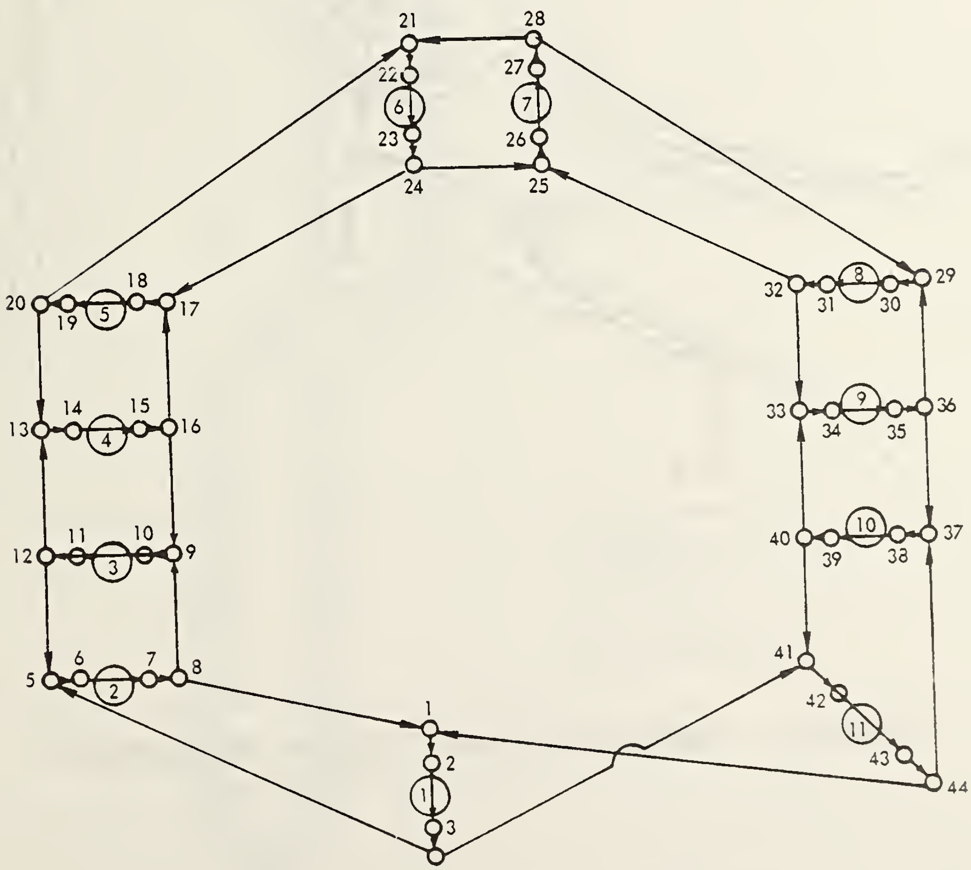


FIGURE A-8. DUAL-LANE LOOP NETWORK MODEL

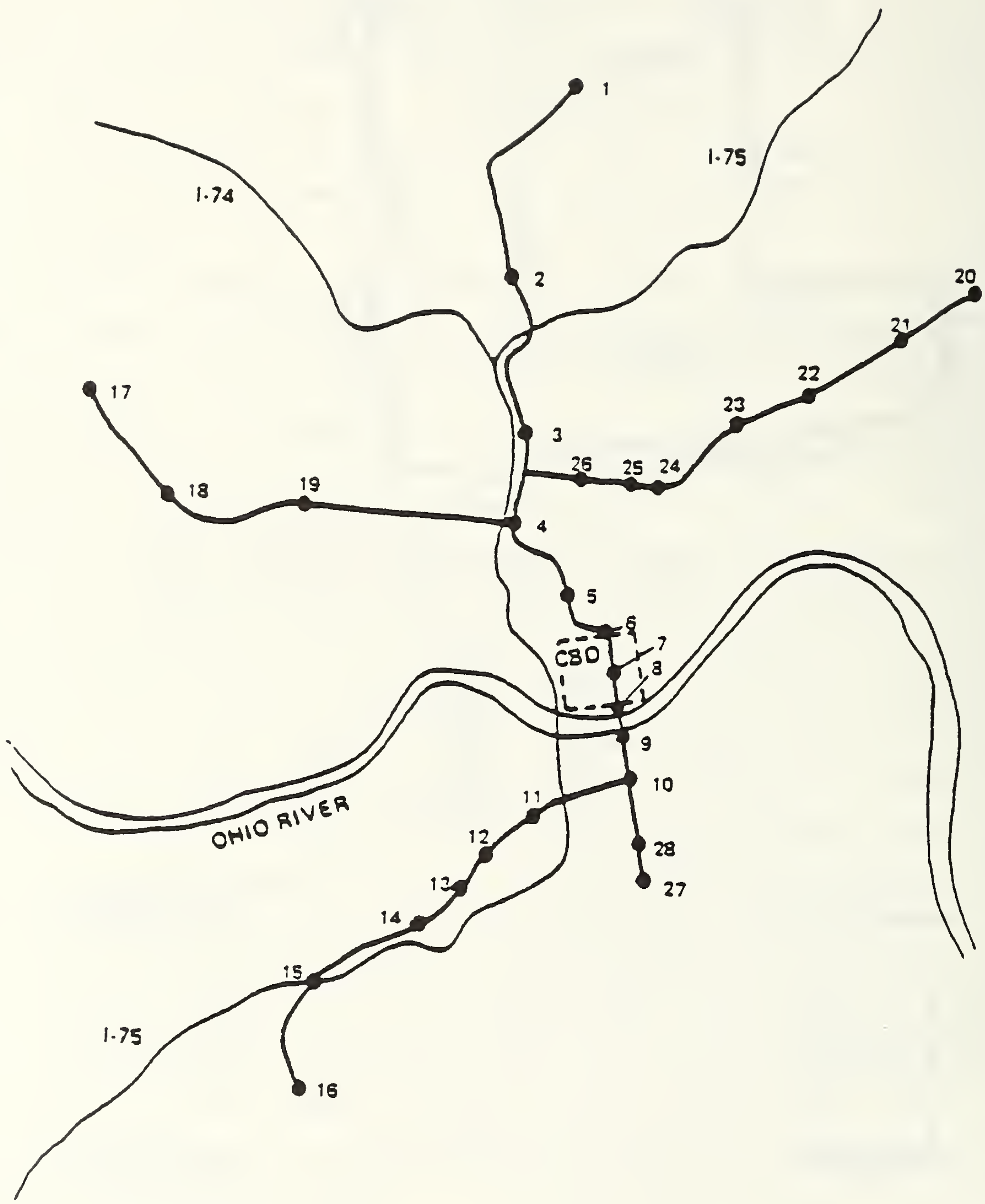


FIGURE A-9. AREA-WIDE LINE-HAUL NETWORK CONFIGURATION

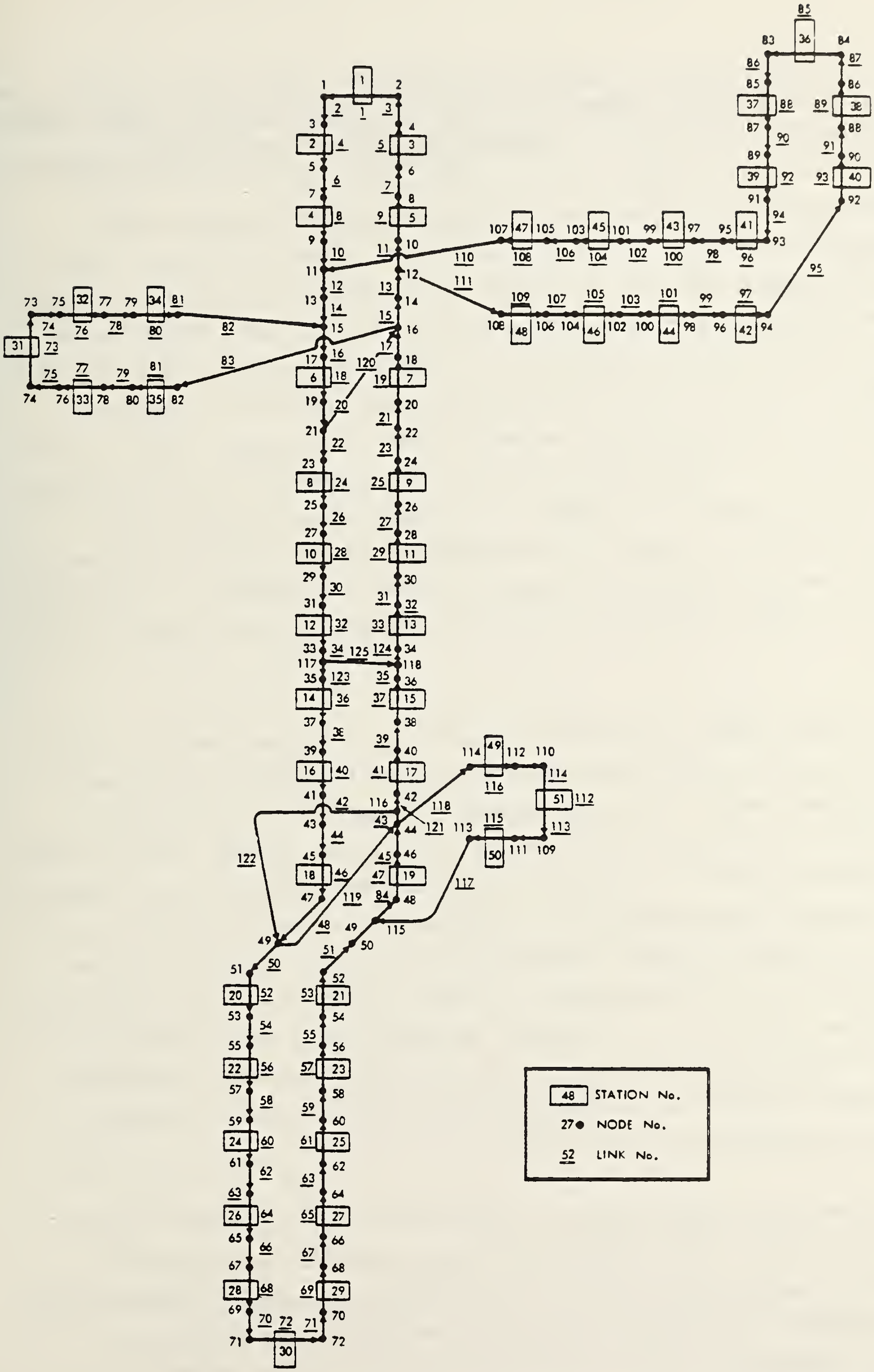


FIGURE A-10. AREA-WIDE LINE-HAUL NETWORK MODEL

are that the dual-lane guideway is modeled as separate inbound and outbound lines and that the stations are modeled as separate inbound and outbound stations except for those located at the end of lines. The dividing of stations into two is necessary to accurately model fixed route system operation as indicated by the first guideline listed in Table 3-2. That guideline states that cyclical routes should be defined so that a station is served by each vehicle only once per cycle. In this case, the 28 actual station locations must be modeled as 51 directional stations to satisfy this guideline. The model also illustrates how extra nodes are included to separate station entry nodes from merge nodes. For example, node 17, the entry node for Station 6, cannot serve as the merge point for links 82 and 14. Therefore, node 15 is added to the network description for this purpose. Similarly, node 16 is added because the exit node for Station 7 cannot serve as a diverge node. Node 16 is also an example of a node which serves as a link entry node for two links and as a link exit node for two links.

The final example illustrates the modeling of a bypass shuttle network similar to that of the Automatically Controlled Transportation System at Fairlane Town Center. The basic network configuration is illustrated in Figure A-11. One model of this network utilizes the station gate algorithm in the DESM and DPMS. The station gate algorithm, which can also be used to model terminal stations designed as switchbacks, permits only one train to enter the station at a time. Any train arriving while a train is in the station must wait on the guideway until the earlier train leaves the station output link. Figure A-12 illustrates the model of the bypass shuttle network which utilizes the station gate algorithm. The dual-lane portion of the network is modeled as a single-lane loop, while the two single-lane segments are modeled as station links.

An example of station design is shown in the figure to help illustrate the model. Travel times on the station input ramp and input queue are specified to model vehicle travel on the single-lane guideway approaching an on-line station. Input and output queues are included to account for possible differences in travel time on the two single-lane segments. Stations can be defined with two input queues and two output queues each

having a different travel time. By making the appropriate queue links unavailable (input parameter SLAVAIL=F) the travel times into and out of each station can be specified individually.

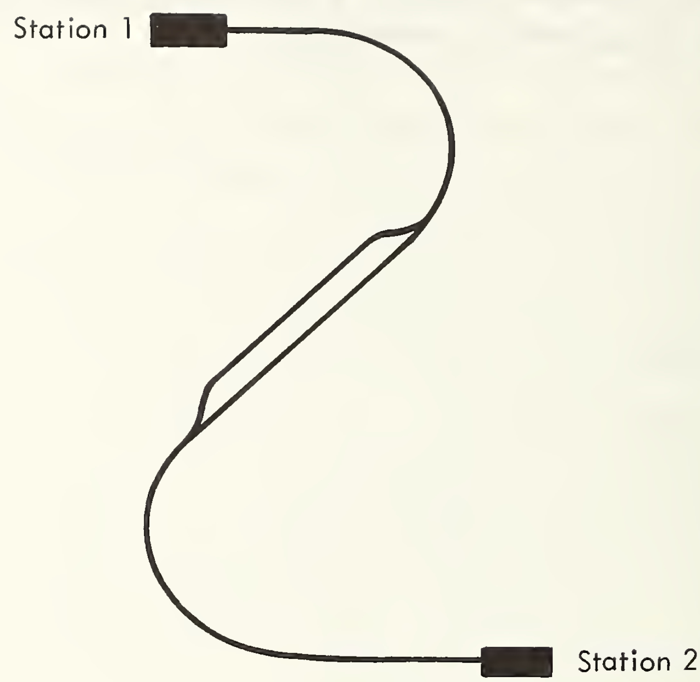


FIGURE A-11. BYPASS SHUTTLE NETWORK CONFIGURATION

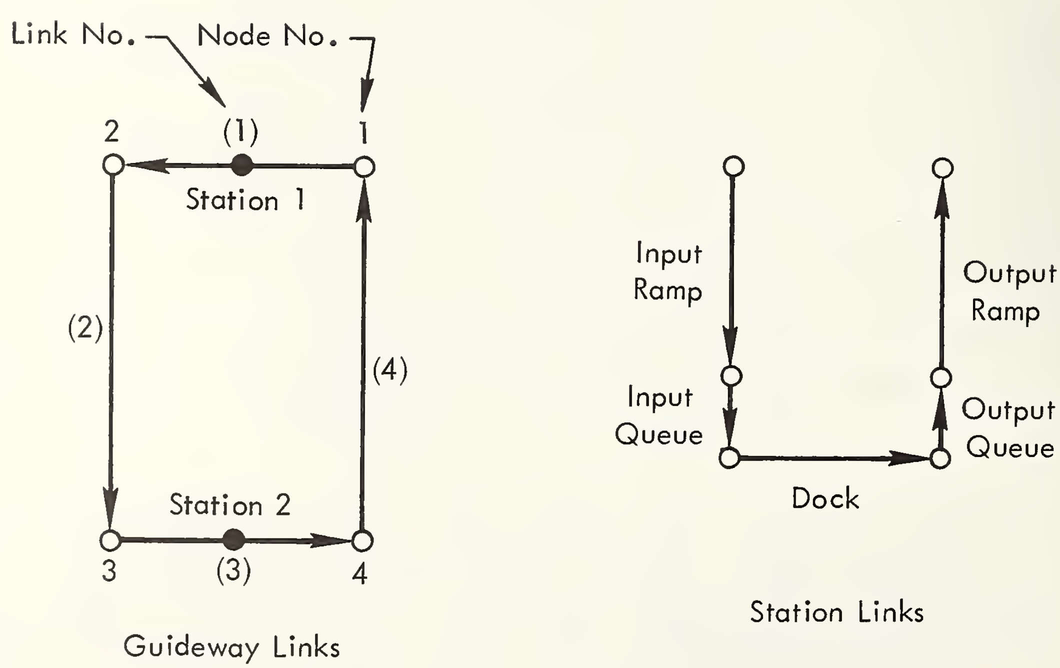


FIGURE A-12. MODEL OF BYPASS SHUTTLE NETWORK

APPENDIX B

VEHICLE ANALYSIS

The objective of the Vehicle Analysis is to define the physical characteristics of AGT vehicles in terms of dimensions, mass, propulsion performance, energy consumption, and noise production. In this appendix correlations which have been developed to estimate vehicle dimensions and mass as a function of vehicle capacity are presented. Procedures which can be used to estimate vehicle propulsive power and performance as well as the application of these procedures to the requirements of several example deployments are described. Procedures and suggested parameter values to be used to calculate vehicle energy consumption and external noise production are presented. The suggested values of vehicle characteristics presented in this section are derived from published characteristics of existing and proposed AGT vehicles. The suggested values are intended to serve as a guide in cases where actual data for specific vehicles are not available.

A classification structure for AGT systems was developed to serve as a guide in selecting a variety of system types for consideration in the System Operation Studies. The system classification was also useful in organizing vehicle data so that nominal values of vehicle characteristics could be established. The classification structure permits existing and proposed AGT systems to be easily and unambiguously classified into one of several distinct classes which emphasize major differences in level of service and general applicability to various urban environments.

Two system parameters (traveling unit capacity and maximum cruise velocity) were selected to define the classes. Traveling unit capacity is the nominal capacity of the minimum train consist. Since in some systems two or more vehicles are permanently coupled in trains, traveling unit capacity rather than vehicle capacity was selected as a classification parameter to more accurately reflect the service capabilities of systems. Vehicle velocity influences service level through its direct effect on travel time. Maximum speed capability also implies a range of applications for which a system may be suited. Maximum operating speed rather than

cruise speed is used as a classification parameter because the former describes a system capability while the latter may refer to a network constraint or deployment option.

The various classes are defined in Table B-1. Three major categories are identified on the basis of traveling unit capacity: Personal Rapid Transit (PRT), Group Rapid Transit (GRT), and Automated Rail Transit (ART). GRT is further partitioned into three distinct ranges of traveling unit capacity -- Small Vehicle GRT (SGRT), Intermediate Vehicle GRT (IGRT), and Large Vehicle GRT (LGRT). The resulting five classes are further divided as appropriate into eight subclasses on the basis of maximum operating velocity. The subclasses are uniquely defined in terms of the classification parameters in Table B-1. The range of minimum headway which is characteristic of systems in each subclass is given in the table. An example of each system class -- either a system which has been deployed or one which is under active investigation -- is also given in the table.

B.1 VEHICLE DIMENSIONS AND MASS

Vehicle mass and frontal area are required to determine vehicle performance and energy consumption. Vehicle length dictates minimum platform length and thus affects station cost. Vehicle floor area may provide a useful measure of passenger comfort when compared to the average number of passengers per vehicle. To estimate these values, correlations of vehicle mass and dimensions with vehicle capacity have been developed based on available data as reported in Appendix A of "Classification and Definition of AGT Systems."[23] Table B-2 summarizes the relevant characteristics of 43 AGT vehicles arranged by system class (PRT, SGRT, IGRT, LGRT, and ART). Vehicle capacity is given in terms of number of seats, total nominal capacity, and the percent of total capacity which is provided in the form of seats. Nominal capacity is the capacity value including seated and standing passengers which is specified by the manufacturer according to a passenger comfort criterion. The average area allotted to each standee is generally at least 2.5 square feet (0.23 square meter). Vehicle dimensions include length, width, height, floor area, and cross-sectional area. Floor area is the product of vehicle length and width

TABLE B-1. GM TSC CLASSIFICATION STRUCTURE

Category	Class	Subclass	Service Type	Minimum Traveling Unit Capacity (Passengers)	Operating Speed (km/hr)	Characteristic Minimum Headway (s)	Example System
PRT	PRT	low speed	non-stop	3-6	13-54	3 or less	Cabinentaxi
		high speed	non-stop	3-6	55+	3 or less	CVS
GRT	SGRT	low speed	multiple-stop	7-24	13-54	3-15	Morgantown
		high speed	multiple-stop	7-24	55+	3-15	UMTA-AGRT
	IGRT	low speed	multiple-stop	25-69	13-54	15-60	Airtrans
		high speed	multiple-stop	25-69	55+	15-90	Unimobile Transporter
	LGRT		multiple-stop	70-109	13-54	50-109	SEA-TAC
ART	ART		multiple-stop	110+	55+	60+	WMATA

Legend

PRT - Personal Rapid Transit
GRT - Group Rapid Transit
SGRT - Small Vehicle GRT
IGRT - Intermediate Vehicle GRT
LGRT - Large Vehicle GRT
ART - Automated Rail Transit

TABLE B-2 (1 of 2). AGT VEHICLE DIMENSIONS

SYSTEM	CAPACITY Seated	Total	% Seated	Length (M)	Width (M)	Height (M)	Area L x W (M^2)	Frontal Area WxH(M^2)	Empty Mass (kg)
PRT - low									
Cabinentaxi	3	3	100	2.3	1.7	1.6	3.91	2.72	900
Aramis	4	4	100	2.3	1.3	1.4	2.99	1.82	650
Aerial Transit	6	6	100	3.65	1.68	1.58	6.13	2.65	2 180
PRT - high									
Aerospace PRT	6	6	100	3.05	1.52	1.52	4.64	2.31	818
Cabtrack	4	4	100	3.05	1.37	1.68	4.18	2.30	600
CVS	4	4	100	3.35	1.6	1.85	5.36	2.96	770
Elan-Sig	4	4	100	3.1	1.8	1.38	5.58	2.48	795
Monocab	6	6	100	2.92	1.68	2.02	4.91	3.39	1 820
SGRT - low									
Minitram	6	12	50	4.6	2.0	2.6	9.2	5.2	2 540
Ford ACT	10	24	41.7	7.54	2.03	2.64	15.31	5.36	6 485
StaRCAR	6	10	60	3.8	2.04	2.74	7.75	5.59	2 770
	10	20	50	4.3	2.04	2.74	8.77	5.59	3 162
H-Bahn	8	17	47	3.45	2.30	2.30	7.94	5.29	4 450
Morgantown	8	15	53.3	4.72	2.03	2.67	9.58	5.42	3 900
Cabinentaxi AGRT	12	12	100	5.2	1.7	1.6	8.84	2.72	2 000
SGRT - high									
GEC	6	15	40	3.55	1.9	2.8	6.75	5.32	3 350
GM DMTS	17	17	100	8.1	2.4	2.5	19.44	6.00	4 865
Rohr DMTS	21	21	100	8.3	2.4	2.7	19.92	6.48	6 704
IGRT - low									
Airtrans	16	40	40	6.4	2.1	3.0	13.44	6.30	6 349
KRT - 100	10	30(20)	50	4.77	2.03	2.67	9.68	5.42	4 100
Rohr "J"	60	60	100	36.9	1.7	2.2	62.7	3.74	12 517
Rohr "K"	36	36	100	29.3	1.7	1.8	49.81	3.06	9 025
Rohr "M"	0	72	0	9.24	2.44	3.25	22.55	7.93	8 389
IGRT - high									
Dashaveyor I	12	40	30	6.7	2.1	3.05	14.07	6.41	6 800
	40	72	55.6	9.1	2.1	3.05	19.11	6.41	9 090
KCV	16	30	53.3	9.1	2.4	3.15	21.84	7.56	6 800
	24	50	48	9.35	2.4	3.15	22.44	7.56	13 500
Kompaktbahn	24	48	50	11.0	2.2	2.5	24.2	5.5	11 000
MAT	16	32	50	6.4	2.2	2.9	14.08	6.38	7 700
Mini - Monorail	4	13	30.8	7.15	2.0	2.4	14.3	4.8	6 200

* Crush Capacity, or 20 Standees Maximum. Assume 20 Nominal Total Passengers

TABLE B-2 (2 of 2). AGT VEHICLE DIMENSIONS

SYSTEM	CAPACITY Seated	Total	% Seated	Length (M)	Width (M)	Height (M)	Area LxW (M^2)	Frontal Area WxH(M)	Empty Mass (kg)
IGRT - high(cont'd)									
NTS	24	50	48	7.5	2.28	3.05	17.10	6.95	7 300
Project 21 RTS	22	37	59.4	8.23	2.4	2.44	19.75	5.86	4 467
Transurban	14	30	46.7	7.5	2.0	3.2	15.0	6.4	9 000
Tridim Aerotrain	36	52	69.2	16.25	1.93	2.59	31.36	5.0	5 895
UMI Transporter	20	30	66.7	6.1	2.29	2.74	13.97	6.27	4 080
URBA 30	30	30	100	9.0	2.0	2.0	18.0	4.0	3 636
VONA	11	25	44	5.3	2.06	3.06	10.92	6.3	4 500
LGRT									
Westinghouse - T	0	100	0	11.05	2.84	3.35	31.38	9.51	9 772
- S	12	102	11.8	11.28	2.84	3.35	32.04	9.51	11 591
ART									
BART	72	170	42.4	22.8	3.2	3.2	72.96	10.24	26 800
Lindenwold	72	120	60	20.57	3.05		62.74		35 400
VAL	68	124	54.8	25.48	2.06	3.25	52.49	6.7	27 000
WMATA	80	208	38.5	23.0	3.09	2.3	71.07	7.11	32 900

in square meters. Cross-sectional area, the product of width and height, is a rough approximation to the vehicle frontal area. Empty vehicle mass is given in kilograms. In some cases when vehicles are always operated in trains, only the lead vehicle is powered. In these cases trailing vehicles can be exceptionally light. To avoid underestimating vehicle mass, only powered vehicles were considered when the correlations were developed. Finally, only systems designed for all-weather operation are considered. Open-air vehicles such as those in the WEDway and the Rohr "N" systems are not included in this analysis.

Both vehicle width and height remain relatively constant within each major system class as illustrated by the data in Table B-2. Table B-3 shows the average vehicle width and height values for each major system class. The standard deviations of the data for each system class are also tabulated. These average values are used to represent vehicle width and height for each system class. Values of frontal area for AGT vehicles were generally not found in the literature surveyed. However, the product of width and height, the cross-sectional area, is a gross approximation to frontal area. In order to improve this approximation, available data on automobile frontal areas are considered. Table B-4 compares cross-sectional area to frontal area for several small cars.[26] The ratios of frontal area to cross-sectional area for these automobiles range from about 80 to 86.5 percent and average 83 percent. The frontal area to cross-sectional area ratios for two transit vehicles, the proposed GM Dual Mode vehicle and the Commer 1500 Minibus, are 93.5[27] and 80.8 percent, respectively. The estimates of frontal area for the five system classes listed in Table B-3 are 83 percent of the product of average vehicle width and height.

To permit consideration of seated capacity in the regression analysis, the systems listed in Table B-2 were grouped into the following three seating capacity categories based on the ratio of the number of seats to total vehicle capacity: 0 to 31 percent seats (5 systems), 38 to 69 percent seats (24 systems), and 100 percent seats (14 systems). Linear regressions were performed using the vehicle mass, length, and floor area data for systems within each category irrespective of system class. Table B-5 summarizes the results. The table gives the ordinate intercept (b), the

slope (m), and the coefficient of correlation (r^2), for the straight line which best relates each vehicle dimension (mass, length, and floor area) to vehicle capacity for each category of seating capacity. The coefficients of correlation range from 0.84 to 0.93 indicating that vehicle mass, length, and floor area are well correlated with vehicle capacity within each seating capacity category. Floor area is the product of length and width, and vehicle width is assumed to be constant for each system class. Therefore, continuity requires that either the equation for length or the equation for area be used and that the other value be obtained from the result using the appropriate value of vehicle width. Since values of vehicle length are likely to figure more prominently in analyses than values of floor area, it is recommended that the length versus capacity equation be used directly to estimate vehicle length.

TABLE B-3. AVERAGE WIDTH AND HEIGHT OF AGT VEHICLES

System Class	Width (m)		Height (m)		Estimated Frontal Area (m^2)
	Average	Standard Deviation	Average	Standard Deviation	
PRT	1.58	0.17	1.63	0.22	2.14
SGRT	2.08	0.22	2.63	0.15	4.54
IGRT	2.12	0.22	2.74	0.43	4.82
LGRT	2.84	N.A.	3.35	N.A.	7.90
ART	3.17	0.13	3.16	0.65	8.31

*The estimated frontal area is 83 percent of the product of vehicle width and height. This factor (0.83) was derived from comparable automobile data.

TABLE B-4. COMPARISON OF AUTOMOBILE CROSS-SECTIONAL AND FRONTAL AREAS

Vehicle	Vehicle Width (M)	Vehicle Height (M)	Cross-Sectional Area - Ac (M^2)	Frontal Area -Af (M^2)	$\frac{Af}{Ac} \times 100\%$ (Percent)
Bond Bug	1.40	1.22	1.71	1.38	80.8
Triumph GT6	1.46	1.20	1.75	1.41	80.5
Special	1.50	1.10	1.65	1.34	81.2
Mazda 1200	1.48	1.39	2.06	1.71	83.1
DAF 55	1.52	1.40	2.13	1.82	85.5
Honda Custom 77	1.47	1.34	1.97	1.63	82.7
Hillman Avenger	1.59	1.42	2.26	1.83	81.0
Citroen GS	1.60	1.35	2.16	1.85	85.6
Commer 1500 Minibus	1.93	2.00	3.86	3.12	80.8
Cortina 3 GXL	1.70	1.32	2.24	1.85	82.4
Vega	1.66	1.30	2.16	1.81	83.9
Reliant Scimitar GTE	1.65	1.34	2.21	1.86	84.1
SAAB 99	1.68	1.44	2.42	1.93	79.8
Renault 12TL	1.64	1.44	2.36	1.94	82.1
Triumph Stag	1.61	1.26	2.03	1.73	85.3
Vauxhall Victor FD	1.70	1.32	2.24	1.93	86.0
Fiat Dino 2400	1.72	1.32	2.27	1.80	79.3
BMW 2800	1.76	1.45	2.55	2.14	83.8
Austin ADO 61	1.70	1.44	2.45	2.08	85.0
Barracuda	1.90	1.29	2.45	2.04	83.2
Jaguar XJ6	1.78	1.28	2.28	1.97	86.5
AVERAGE					83

TABLE B-5. LINEAR REGRESSIONS OF AGT VEHICLE DIMENSIONS VERSUS VEHICLE CAPACITY

Regression	0-31% Seats (5 Systems)			38-69% Seats (24 Systems)			100% Seats (14 Systems)		
	b	m	r^2	b	m	r^2	b	m	r^2
Mass vs. Capacity	5044.38	53.61	.89	967.11	175.32	.85	191.20	209.40	.90
Length vs. Capacity	5.67	0.05	.90	3.40	0.12	.84	-0.63	0.61	.88
Floor Area vs. Capacity	8.62	0.22	.92	3.65	0.38	.93	-0.71	1.06	.92

The vehicle floor area data and the regression lines are illustrated in Figure B-1. According to intuition, as the percent seats is increased for any given vehicle capacity, the floor area should also increase because seated passengers generally require more area than do standees. However, for vehicle capacities between 10 and 32 passengers, the regression equations result in higher estimates of floor area for vehicles in the 0-31 percent seats class than for vehicles in the 38-69 percent seats class. The data indicate that vehicles with capacities of less than 10 passengers permit no standees. The anomaly occurs in low capacity vehicles where the propulsion and communication systems can require a significant portion of vehicle area. This area, when located at the ends of the vehicle, cannot be used for standees but frequently can be used to seat passengers, thereby increasing vehicle capacity without increasing area. Since vehicle length is directly proportional to area, the intuitive result of increased length for increased percent seats and the anomaly at low vehicle capacities can be expected. Figure B-2 illustrates the data and the results of the regression analysis involving vehicle length. If vehicle mass is also related to area, similar results can be expected in the mass-capacity correlations. Figure B-3 shows the vehicle mass data plotted against vehicle capacity. The regression lines for the three categories of seating capacity are also shown in the figure.

In summary, an average value of vehicle height, width, and frontal area was determined for each system class. Vehicle mass and vehicle length are expressed as linear functions of vehicle capacity for each of three categories of seating capacity. Vehicle floor area can be estimated as the product of vehicle length and width.

B.2 VEHICLE PROPULSIVE POWER AND PERFORMANCE

An estimate of vehicle performance is a fundamental input to the system analysis. Acceleration/deceleration capability often limits the cruise velocity which can be specified on links between closely-spaced, on-line stations. The performance capability of the vehicle clearly impacts the time and distance required for acceleration and deceleration maneuvers. The

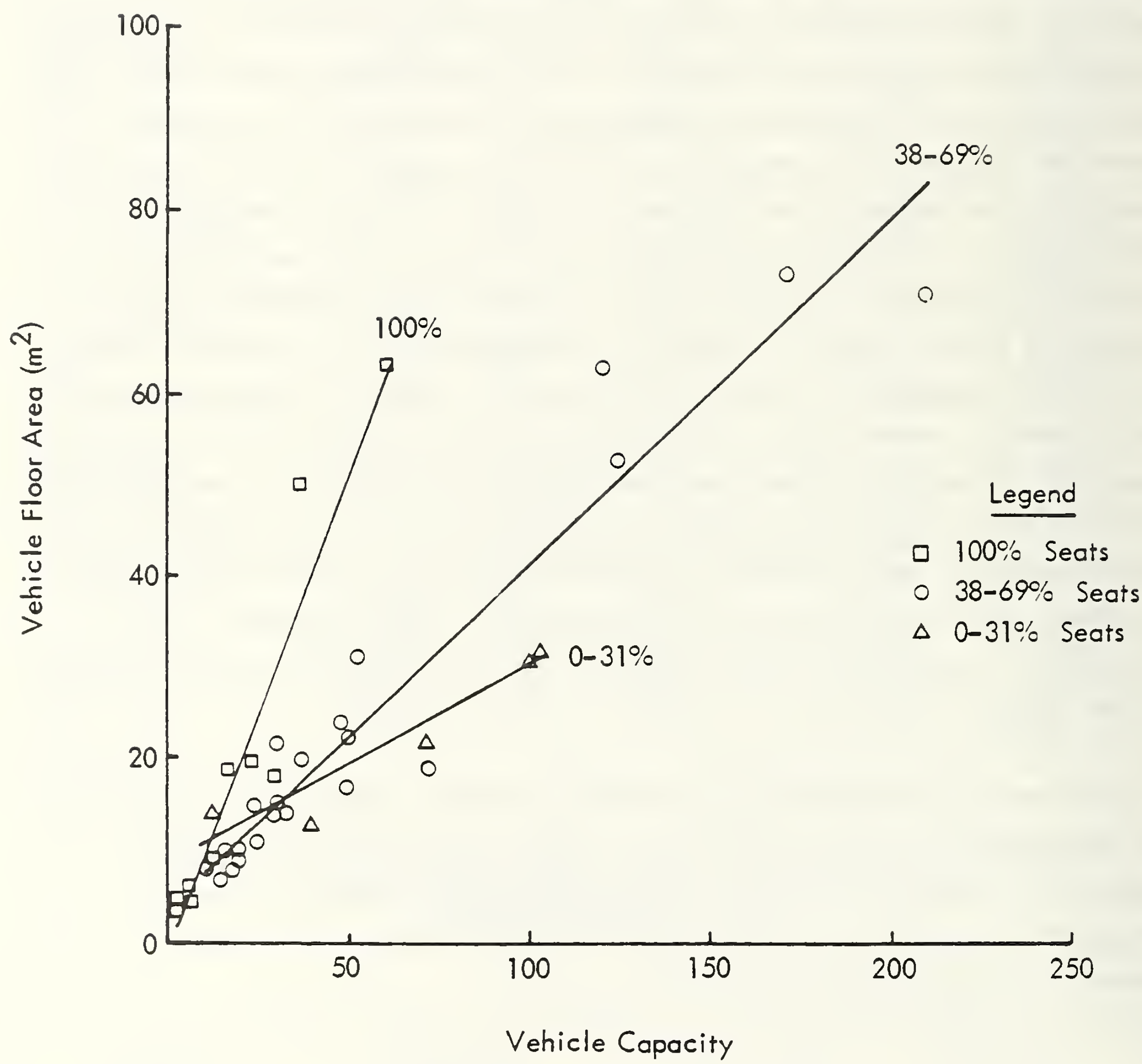


FIGURE B-1. VEHICLE FLOOR AREA VERSUS CAPACITY

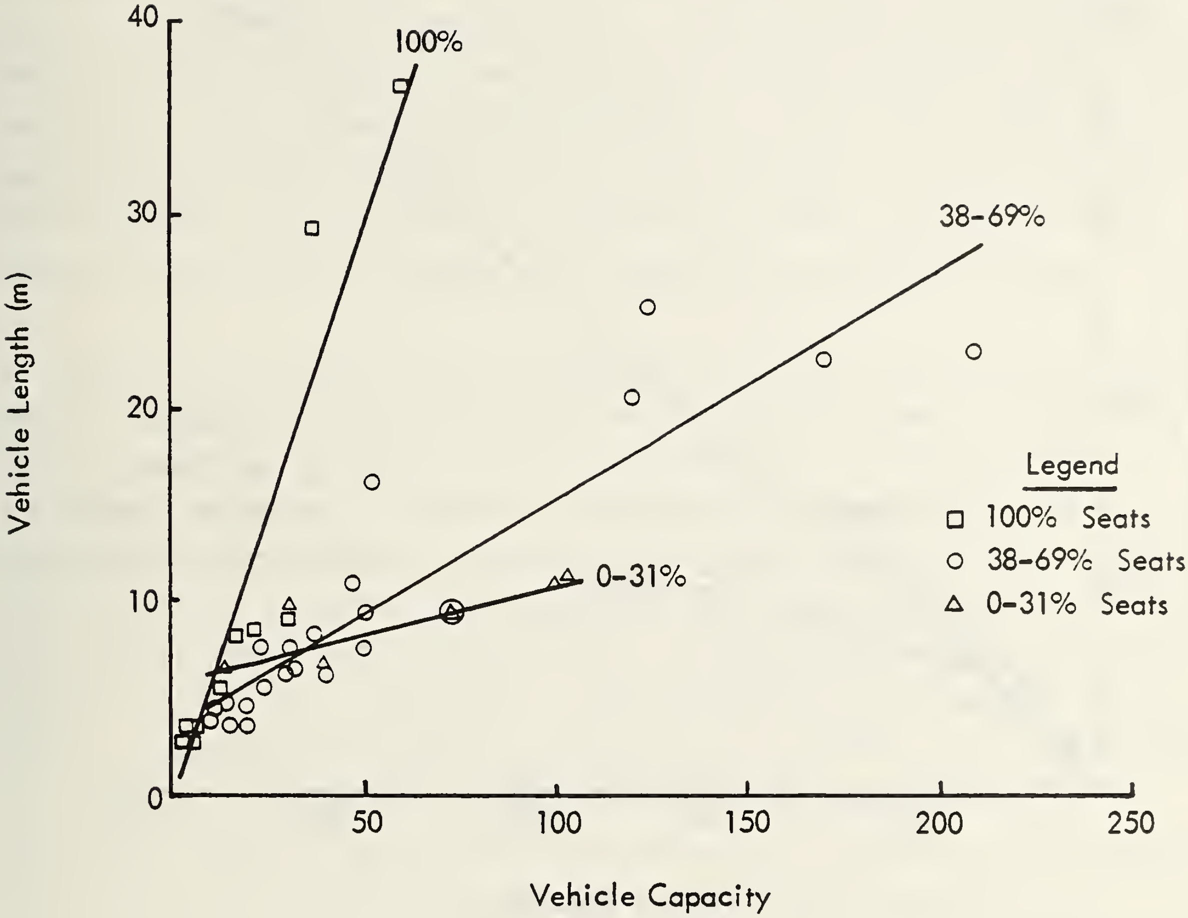


FIGURE B-2. VEHICLE LENGTH VERSUS CAPACITY

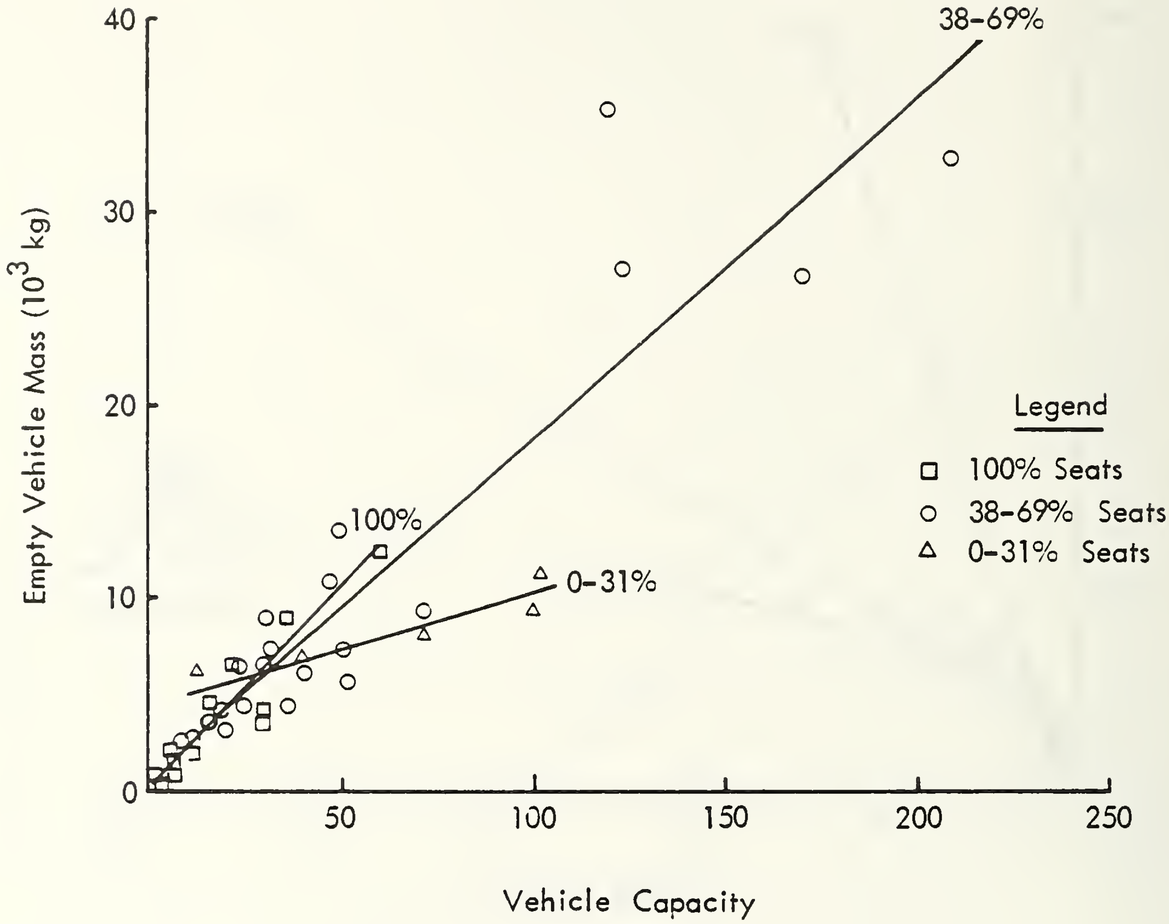


FIGURE B-3. EMPTY VEHICLE MASS VERSUS CAPACITY

purposes of this phase of the analysis are to specify an acceleration profile for each vehicle based on comfort and propulsive power limits and to evaluate the equations of motion to define the limits of vehicle performance capability. In this section suggested values of vehicle and environmental parameters and equations which can be used to calculate vehicle performance are presented. The equations are evaluated for several representative vehicles, and results are presented in the form of parametric curves.

In order to estimate vehicle performance an acceleration versus velocity profile must be established for each vehicle based on propulsive power and maximum acceleration constraints. In the absence of actual vehicle performance data, one of several different acceleration profiles can be assumed. In many analyses, constant acceleration has been assumed. This profile results in simplified equations for acceleration time and distance, but it often requires an unrealistically high propulsive power capability or a very low level of acceleration. The power required to maintain a given level of acceleration increases as the velocity increases. Thus, unless the acceleration is specified at a very low level, the power required to maintain a constant acceleration as the velocity is increased from zero to the nominal cruise velocity is often much higher than that which is available. An alternate acceleration-velocity profile, which is recommended for use in estimating vehicle performance, results in reasonable acceleration capability within assumed power constraints. The general profile is illustrated by example in Figure B-4 which shows an assumed acceleration profile for a 70-passenger LGRT vehicle with 0 to 31 percent seats. The maximum acceleration constraint (a_m), which may be dictated by comfort criteria or other considerations, is 1.0 m/s^2 in this example. This level of acceleration is maintained up to the velocity (V_1) at which the required propulsive power equals that available at the wheels (which, in this case, is assumed to be 106 kW). For velocities greater than V_1, the commanded acceleration is defined by the straight line connecting the points of maximum acceleration at V_1 and the maximum acceleration capability of the vehicle at V_c, the cruise velocity. The profile is determined by solving the propulsive power equation given below.

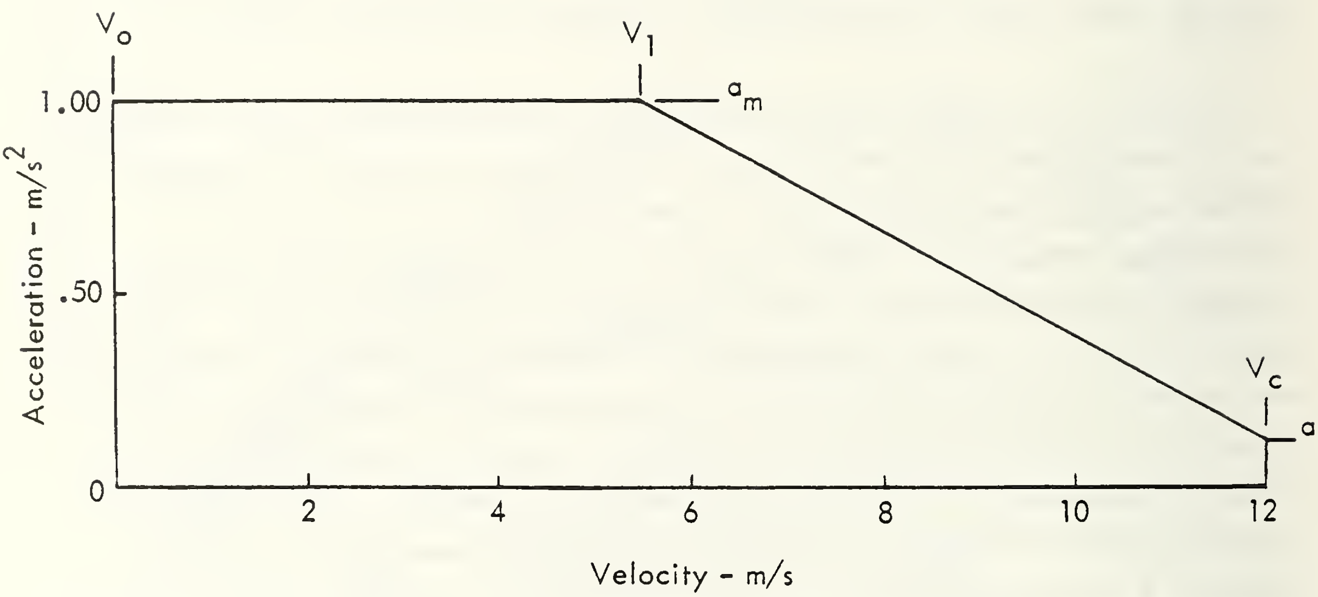


FIGURE B-4. SAMPLE ACCELERATION PROFILE

70 Passenger LGRT Vehicle
Seating Capacity: 0–31%
Vehicle Mass, Empty: 8797 kg
Loaded: 13,559 kg
Nominal Propulsive Power: 106 kW
Acceleration Time: 20.8 s
Acceleration Distance: 164.8 m

$$P = Mav + 1/2\,\rho C_D A * SGN\,(v + V_w) * v\,(v + V_w)^2 + C_R M V^2 + (C_s M + MgG/100)\,v \tag{B-1}$$

where P = propulsive power (w)

a = vehicle acceleration (m/s^2)

ρ = air density ($\frac{kg}{m^3}$)

C_D = drag coefficient (n.d.)

A = frontal area (m^2)

SGN( ) = sign of ( ) : + 1 or -1

v = vehicle velocity (m/s)

V_w = wind velocity (m/s), headwind positive

C_S = static coefficient ($\frac{N}{kg}$)

C_R = rolling coefficient ($\frac{Ns}{kgm}$)

M = vehicle mass (kg)

g = acceleration of gravity (9.80 m/s^2)

G = percent grade

The first term represents the acceleration power requirement; the second term represents aerodynamic drag; the third term represents rolling resistance; and the fourth term represents the combined effects of static friction and guideway grade. A more compact expression of the same equation is as follows:

$$P = Mav + C_1 v + C_2 v^2 + C_3 v^3 \tag{B-2}$$

where

$$C_1 = 1/2\,\rho C_D A\,(V_w)^2\ SGN(v + V_w) + C_s M + MgG/100\ (N) \tag{B-3}$$

$$C_2 = C_R M + \rho C_D A\,V_w\ SGN(v + V_w)\ (N\ s/m) \tag{B-4}$$

$$C_3 = 1/2\,\rho C_D A\ SGN(v + V_w)\ (N\ s^2/m^2) \tag{B-5}$$

$$\rho = \frac{353\ p}{273 + T} \quad (kg/m^3) \tag{B-6}$$

p = atmospheric pressure (atmospheres)

T = temperature (C)

The maximum velocity (V_1) at which the maximum acceleration (a_m) can be maintained is the positive real root of the propulsive power equation (B-2). The maximum speed capability of the vehicle is the positive real root of Equation (B-2) when the acceleration (a) is set equal to zero. For a cruise velocity other than the maximum speed capability of the vehicle, the maximum final acceleration (a_f) corresponding to the cruise velocity (V_c) is determined by solving Equation (B-2) for acceleration (a) as follows:

$$a_f = \left[P - C_1V_c - C_2V_c^2 - C_3V_c^3\right] / \ (MV_c) \tag{B-7}$$

where a_f = maximum final acceleration corresponding to the cruise velocity (V_c) (m/s²)

V_c = cruise velocity (m/s)

The time and distance required to accelerate from an initial velocity (V_o) to the cruise velocity (V_c) according to the acceleration profile is given by the following sets of equations:

For $V_c \leq V_1$

$$t_a = (V_c - V_o) / a_m \tag{B-8}$$

$$X_a = (V_c^2 - V_o^2) / (2\ a_m) \tag{B-9}$$

For $V_c > V_1$

$$t_a = t_1 - \frac{1}{a} \ln \left(\frac{b - aV_c}{b - aV_1}\right) \tag{B-10}$$

$$X_a = X_1 - \frac{Vc - V_1}{a} - \frac{b}{a^2} \ln \left(\frac{b - aV_c}{b - aV_1}\right) \tag{B-11}$$

where

t_a = time required to accelerate from an initial velocity to the cruise velocity (s)

X_a = distance traveled in accelerating from an initial velocity to the cruise velocity (m)

V_c = cruise velocity (m/s)

V_o = initial velocity (m/s)

V_1 = maximum velocity for which maximum acceleration (a_m) can be maintained (m/s)

a_m = maximum acceleration constraint (m/s²)

t_1 = time required to accelerate from V_o to V_1 (s)

X_1 = distance traveled in accelerating from V_o to V_1 (m)

a = $(a_m - a_f) / (V_c - V_1)$ (1/s)

b = $(a_m V_c - a_f V_1) / (V_c - V_1)$ (m/s^2)

If service deceleration depends on dynamic braking achieved by reversing the field in the electric drive motors, then braking maneuvers are power limited in the same way that acceleration is constrained, and the same equations apply for calculating deceleration time and distance. However, most vehicles depend on mechanical friction brakes or on a combination of friction and dynamic braking. Therefore, it is not unreasonable to assume that service braking can be accomplished at constant deceleration. The following simple equations give deceleration time and distance assuming a constant level of deceleration:

$$t_d = V_c/d_s \qquad \text{(B-12)}$$

$$X_d = V_c^2/2d_s \qquad \text{(B-13)}$$

where

t_d = Time required to stop (s)
V_c = Cruise velocity (m/s)
d_s = Service deceleration (m/s^2)
X_d = Stopping distance (m)

In order to establish acceleration profiles and to evaluate acceleration times and distances, values of vehicle and environmental parameters must be specified. Values of empty vehicle mass and frontal area can be specified using the relationships presented in the previous section. Values of the three vehicle retardation coefficients, C_D, C_S, and C_R, which have been obtained from previous studies as well as suggested values for the coefficients are listed in Table B-6. The suggested values are representative of rolling resistance and drag coefficients for rubber-tired AGT vehicles except where noted in the table.

TABLE B-6. ROLLING RESISTANCE COEFFICIENTS FOR AGT VEHICLES

Coefficient	SOURCE Knutrud[28]	DMTS[29]	Buckle[30]	Marks[31]	Garrard & Caudill[32]	Suggested Value
C_D	.738*	.50	(.65)**	.38-.55		0.65
C_S	.0464 (.0093)**	.0853	(.0262)**		.03385	0.065 (.01775)**
C_R	0	.00375			.00058	0.00375 (.00033)**

* Estimated assuming the vehicle frontal area is 83% of the vehicle width (4.33 ft) times height (5.80 ft.).

** For trains with steel wheels on steel rails.

The propulsive power constraint for each vehicle is a necessary input for the calculation of acceleration profiles. If the characteristics of the particular vehicles under consideration are not known, then propulsion limits can be estimated based on typical characteristics of AGT vehicles. In the System Operations Studies, a number of hypothetical vehicle designs were considered. In that project a representative level of maximum propulsive power was established for each system class based on the reported characteristics of existing and proposed AGT systems. The reference data and a description of the analysis which led to the selection of the representative values are presented here.

Table B-7 summarizes the power and vehicle mass of 14 low speed AGT vehicles, and Table B-8 summarizes similar data for 22 high speed AGT vehicles. The loaded vehicle mass in Table B-7 is determined by assuming the vehicle is filled to capacity with passengers whose average mass is 68 kg (150 lb). The ratios of propulsive power to vehicle mass typically vary over a wide range even within each system class. Figure B-5 shows propulsive power plotted against empty vehicle mass for low speed AGT systems. One point (10 -- Rohr J and K series) represents vehicles having an extremely low power to mass ratio. A least squares regression line through the data with this point (10) omitted is shown in the figure. The coefficient of correlation for this regression is 0.33 which indicates a generally poor correlation. However, since the line appears to be representative of the data, it was used to select nominal propulsive power limits for low speed GRT vehicles in the System Operations Studies. The selected power limit for each system class was based on the mass of a representative vehicle in each class. The values of propulsive power which were selected to define acceleration profiles for low speed AGT systems in the AGTT-SOS analysis are 106 kW for LGRT, 65 kW for IGRT, 47 kW for SGRT, and 20 kW for PRT.

In an initial attempt to define a value of propulsive power for high speed PRT and GRT systems, a least squares fit of the PRT and GRT data was developed. The regression line is defined by the following equation:

$$P = .014M + 35.22 \qquad \text{(B-14)}$$

where

P = propulsive power in kilowatts

M = empty vehicle mass in kilograms.

TABLE B-7. PROPULSIVE POWER CHARACTERISTICS OF LOW-SPEED AGT SYSTEMS

System	Power kW	Empty Vehicle Mass kg	kW/kg	Loaded Vehicle Mass/kg	kW/kg
LOW SPEED PRT					
1 Aramis	20	650	.03	922	.022
2 Aerial Transit System	37.4	2 180	.02	2 588	.014
LOW SPEED SGRT					
3 Minitrain	40	2 540	.02	3 356	.012
4 StaRRcar	74.6	2 770	.03	3 450	.022
5 Ford ACT	89.6	6 485	.01	8 117	.011
6 H-Bahn	34	4 450	.01	5 606	.006
7 Morgantown	52.2	3 900	.01	4 920	.011
LOW SPEED IGRT					
8 Airtrans	44.7	6 349	.01	9 069	.005
9 KRT-100	50.0	4 100	.01	11 448	.002
10 Rohr J and K	18.7	9 000	.002	13 285	.003
11 Rohr M	37.3	8 389	.004		
12 UMI Tourister	6.7	1 088	.01	2 448	.003
LOW SPEED LGRT					
13 Westinghouse-Tampa	78	9 772	.01	16 572	.005
14 Westinghouse-SEATAC	74.6	11 591	.006	18 527	.004
AVERAGE			.013		.009

TABLE B-8. PROPULSIVE POWER CHARACTERISTICS OF HIGH-SPEED AGT SYSTEMS

System	Power kW	Vehicle Capacity	Empty Vehicle Mass kg	kW/kg
High Speed PRT				
1 Cabtrack	25	4	600	.042
2 CVS	16	4	770	.021
3 Elan Sig	15	4	795	.019
4 Monocab	30	6	1,820	.016
High Speed SGRT				
5 GEC	70.4	15	3,350	.021
6 GM DMTS	238	17	4,865	.049
7 Rohr DMTS	187	21	6,704	.028
High Speed IGRT				
8 Dashaveyor	93	72	7,945	.012
9 KCV	100	40	10,150	.010
10 Kompactbahn	150	48	11,000	.014
11 MAT	65	32	7,700	.008
12 Mini-Monorail	60	38	9,700	.006
13 Project 21	89	37	4,467	.020
14 Transurban	300	30	9,000	.033
15 Tridin Aerotran	150	52	5,895	.025
16 Unimobile Transporter	119	34	4,080	.029
17 UR3A	160	30	3,636	.044
18 VONA	55	25	4,500	.012
ART				
19 BART	416	170	26,800	.015
20 PATCO	416	125	34,776	.012
21 VAL	360	160	27,000	.013
22 WMATA	524	208	32,900	.016

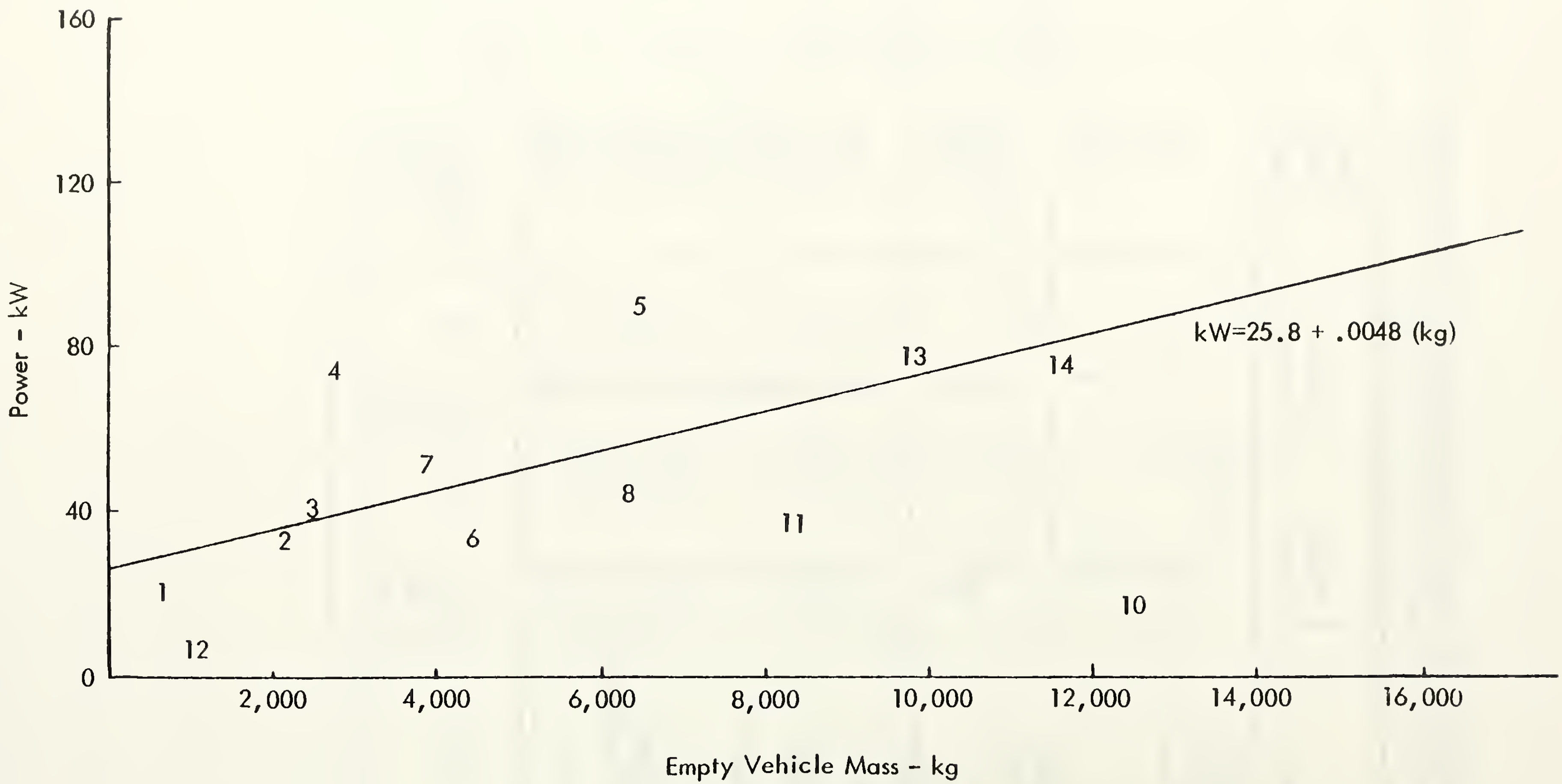


FIGURE B-5. PROPULSION SYSTEM POWER VERSUS EMPTY VEHICLE MASS FOR LOW-SPEED SYSTEMS

Use of this relationship to establish power limits for high speed PRT vehicles results in a value which is too large compared to the data listed in Table B-8. On the other hand, use of the relationship to establish propulsive power limits for high speed SGRT and IGRT vehicles results in relatively low performance capability for these vehicles. For example, the propulsive power of a 24-passenger, high speed SGRT vehicle having an empty vehicle mass of 5175 kg (estimated using the correlation given in Table B-5 for 38 to 69 percent seats) would be 107 kW. according to the regression equation. This level of power permits this SGRT vehicle to reach a maximum cruise velocity of only about 22 m/s assuming a 3 percent grade and a 13 m/s headwind. An alternate approach to establishing a nominal value of propulsive power is to require that a vehicle be able to achieve some minimum level of maximum velocity. This approach was used in the System Operations Studies to establish nominal power levels for high speed GRT vehicles. It was required that the largest vehicle in each class (SGRT or IGRT) be able to achieve a maximum velocity of 25 m/s. This resulted in power constraints of 200 kW for high speed SGRT vehicles and 275 kW for high speed IGRT vehicles. As illustrated in Figure B-6, these values are near the maximum values observed for vehicles in the two classes.

In the ART analysis conducted as a part of the SOS program, the propulsion power characteristic of WMATA vehicles (524 kW) was selected to represent the ART class. The average propulsive power associated with PRT vehicles is between 19 and 24 kW depending whether or not the larger PRT vehicles are considered. In the preliminary analysis of PRT systems conducted during the SOS program, a propulsive power level of 20 kW was assumed for both low speed and high speed PRT systems.

In the DESM it is assumed that the vehicle can always achieve the cruise velocity which is specified. Therefore, when specifying commanded vehicle performance, a worst case combination of vehicle mass, headwind, and guideway grade should be considered. A usual specification for steady wind velocity used in AGT system design studies is 13.4 m/s (30 mi/h). In the System Operations Studies the acceleration profiles were determined assuming a headwind velocity of 13 m/s. The maximum guideway grade to be considered in specifying the acceleration profile depends on the vertical alignment of

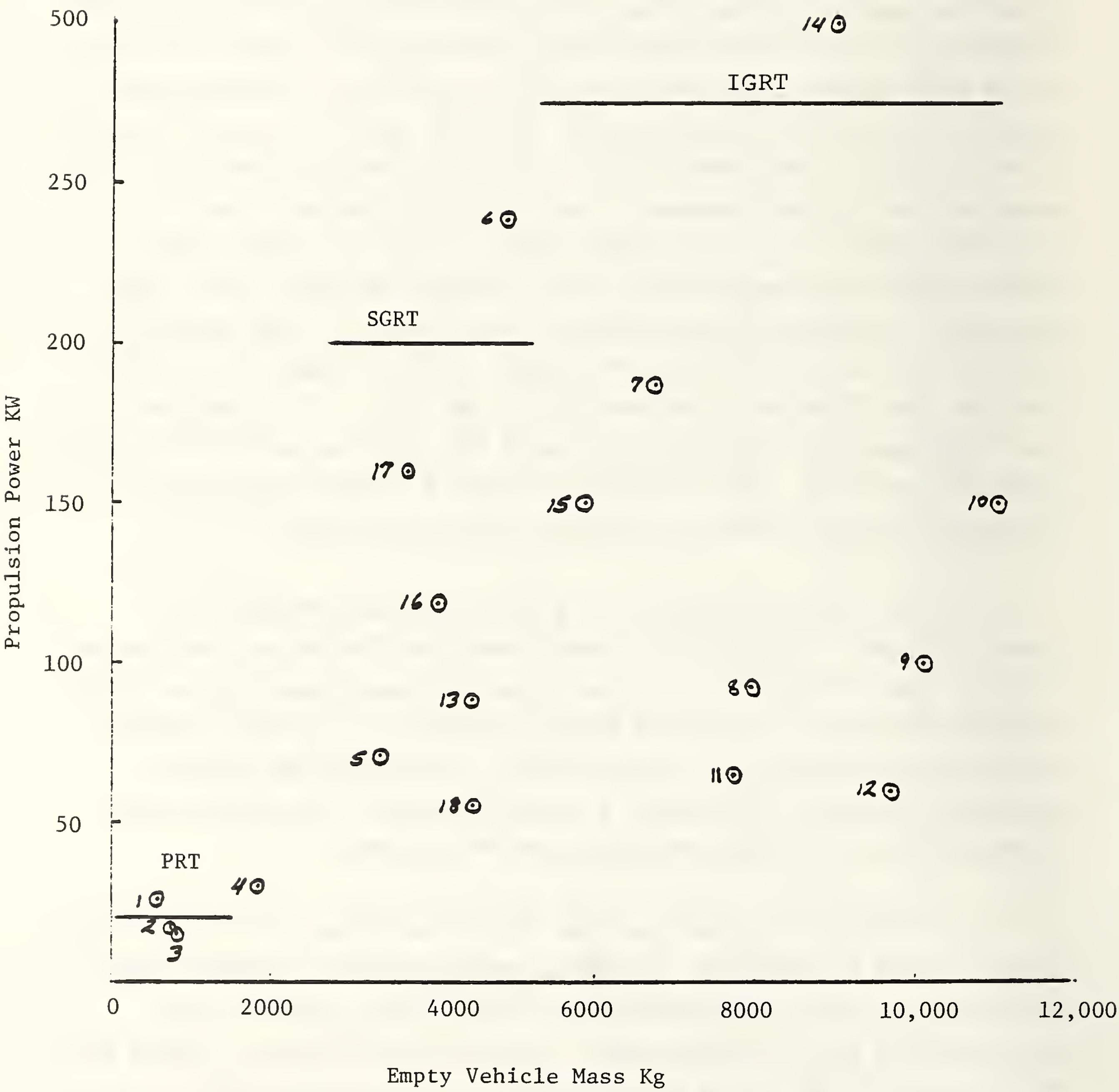


FIGURE B-6. PROPULSION POWER VERSUS EMPTY VEHICLE MASS FOR HIGH-SPEED AGT SYSTEMS

the guideway under investigation. In order to maintain the specified velocity, it is necessary that the vehicles have some excess acceleration capability when traveling at the specified cruise speed up the steepest grade in the network. However, it is not always necessary to consider the steepest grade when the nominal acceleration profile is being determined. For the purposes of this calculation, it is sufficient to consider the steepest grade in a region of the network in which an acceleration maneuver is regularly performed. In the System Operations Studies, a guideway grade of 3 percent was used as a worst case condition under which vehicles should be capable of maintaining the specified acceleration profile while fully loaded and operating in the presence of a 13 m/s headwind.

The reported acceleration and service deceleration capabilities of low speed GRT vehicles are in the range of 0.6 to 1.3 m/s^2. A nominal value of 1.0 m/s^2 is a representative one for these low speed systems. PRT and high speed SGRT systems are generally capable of higher performance according to the reported capabilities of these systems.[23] A value of 2.2 m/s^2 is reasonable for both acceleration and service deceleration for these systems since the range of reported values is 1.2 to 2.5 m/s^2. The larger high speed vehicles (IGRT and ART) appear to have lower acceleration capability than the smaller-vehicle systems (0.5 to 1.7 m/s^2 range). Therefore, the lower value of 1.0 m/s^2 for acceleration and service deceleration is suggested for high speed IGRT and ART systems.

Representative values of vehicle performance parameters and environmental conditions are summarized for each of eight classes of AGT systems in Table B-9. Equations B-1 through B-11 establish acceleration profiles and give vehicle performance. Loaded vehicle mass can be calculated as a function of vehicle capacity using the relationships given in Table B-5 and an assumed average passenger mass (e.g., 68 kg). Service deceleration time and distance can be calculated using Equations B-12 and B-13 assuming a constant level of deceleration.

Figure B-7 illustrates the effect of vehicle capacity on acceleration time and distance for low speed SGRT vehicles with 38-69 percent seats. Data of this nature is used in determining round-trip travel times on routes

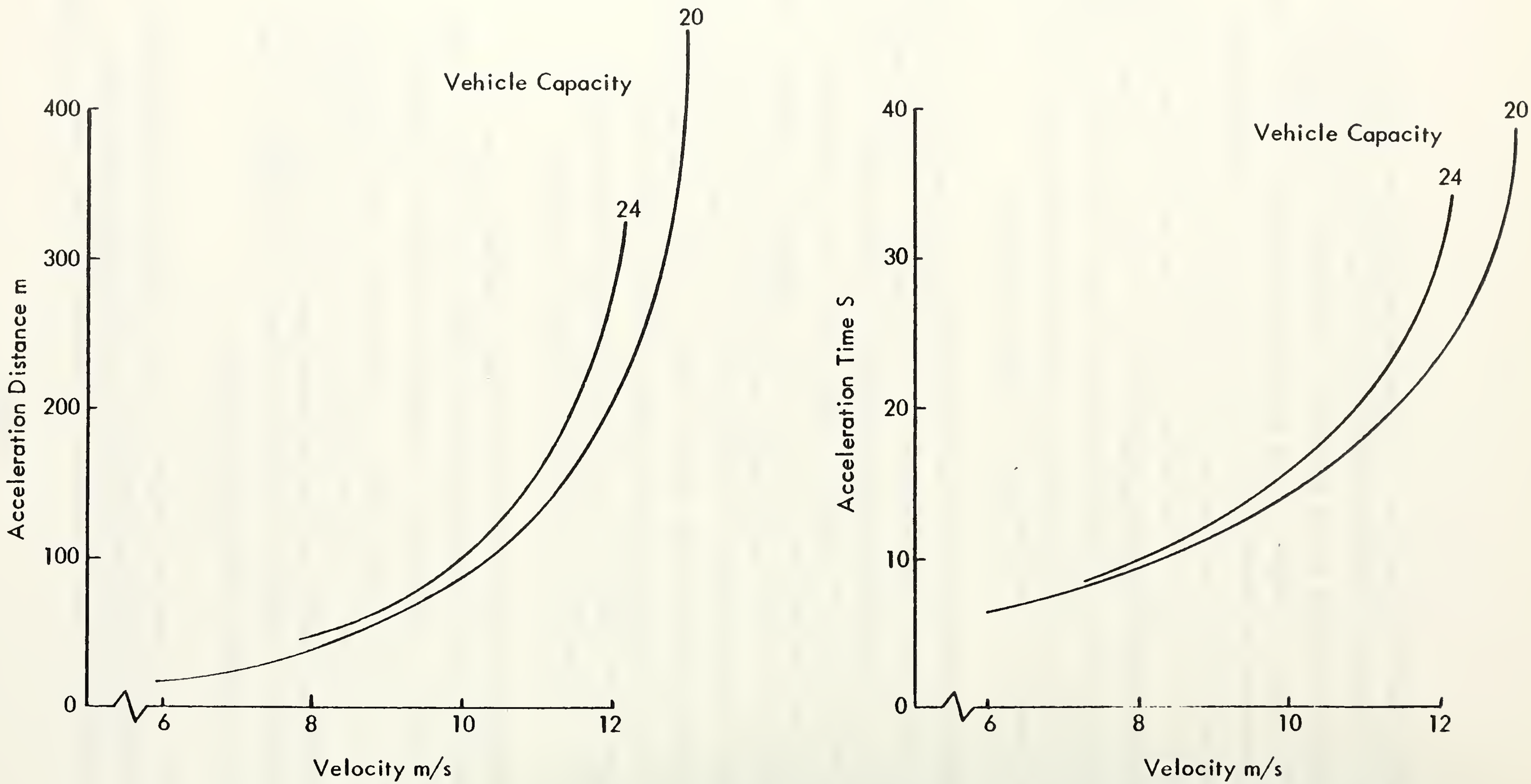


FIGURE B-7. ACCELERATION DISTANCE AND TIME VERSUS VELOCITY FOR SGRT VEHICLES WITH 38-69% SEATS

TABLE B-9. REPRESENTATIVE VALUES OF VEHICLE PERFORMANCE PARAMETERS

	Parameter	Units	LS PRT	LS SGRT	LS IGRT	LS LGRT	HS PRT	HS SGRT	HS IGRT	ART
			Parameter Values							
A_f	Vehicle Frontal Area	m^2	2.14	4.54	4.82	7.90	2.14	4.54	4.82	8.31
P	Propulsive Power Limit	kW	20	47	65	106	20	200	275	524
A_m	Maximum Acceleration	m/s^2	2.2	1.0	1.0	1.0	2.2	2.2	1.0	1.0
d_s	Service Deceleration	m/s^2	2.2	1.0	1.0	1.0	2.2	2.2	1.0	1.0
C_d	Aerodynamic Drag Coefficient	-	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
C_r	Rolling Resistance Constant	Ns/kg m	0.00375	0.00375	0.00375	0.00375	0.00375	0.00375	0.00375	.00033
C_s	Static Resistance Constant	N/kg	0.040	0.040	0.040	0.040	0.040	0.040	0.040	.018
V_w	Wind Velocity	m/s	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
G	Guideway Grade	%	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
P	Atmosphere Pressure	atm	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
T	Air Temperature	C	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0

and station acceleration lane lengths. Figure B-8 shows acceleration distance as a function of velocity for low speed IGRT vehicles of various capacities with 38-69 percent seats. Figure B-9 shows acceleration time versus velocity for the same set of IGRT vehicles. Figures B-10 and B-11 illustrate the effect of variations in percent seats on acceleration performance of 58-passenger IGRT vehicles. The maximum velocity shown for each seating capacity class corresponds to the maximum speed capability of each vehicle due to propulsive power limitations. The data show that the maximum speed capability of 58-passenger low speed IGRT vehicles, under the assumed conditions of wind and grade is about 12 m/s for vehicles with 0-31 percent seats and only about 8.6 m/s for vehicles with 100 percent seats. The difference in vehicle performance is due entirely to the difference in vehicle mass. The acceleration performance characteristics (distance and time) of various LGRT vehicles are shown as a function of velocity in Figure B-12. The data are for vehicles in the 0-31 percent seats category. The effect of percent seats on the acceleration performance of LGRT vehicles is illustrated in Figure B-13. Acceleration time and distance for various high speed GRT vehicles are illustrated in Figures B-14 and B-15, respectively.

Maximum cruise velocity on guideway links between on-line stations can be constrained by short station spacing when limited acceleration capability is taken into account. Figure B-16 shows the total distance required to accelerate and decelerate as a function of velocity for 58-passenger, low speed vehicles having various seating capacities. The horizontal lines indicate the distance between three sets of closely spaced stations in a hypothetical CBD Circulation application. The figure shows, for example, that although the 38-69 percent seats vehicle is ultimately capable of accelerating to about 9.7 m/s, the distance between Stations 10 and 11 limits the maximum velocity on this link to about 8.9 m/s. Limitations of this nature should be considered in specifying link velocities to be used in simulating the operation of AGT systems.

B.3 VEHICLE ENERGY CONSUMPTION

Vehicle energy consumption is one component of variable cost. The methodology and parameters used to calculate vehicle energy consumption for both auxiliaries and propulsion are presented in this section.

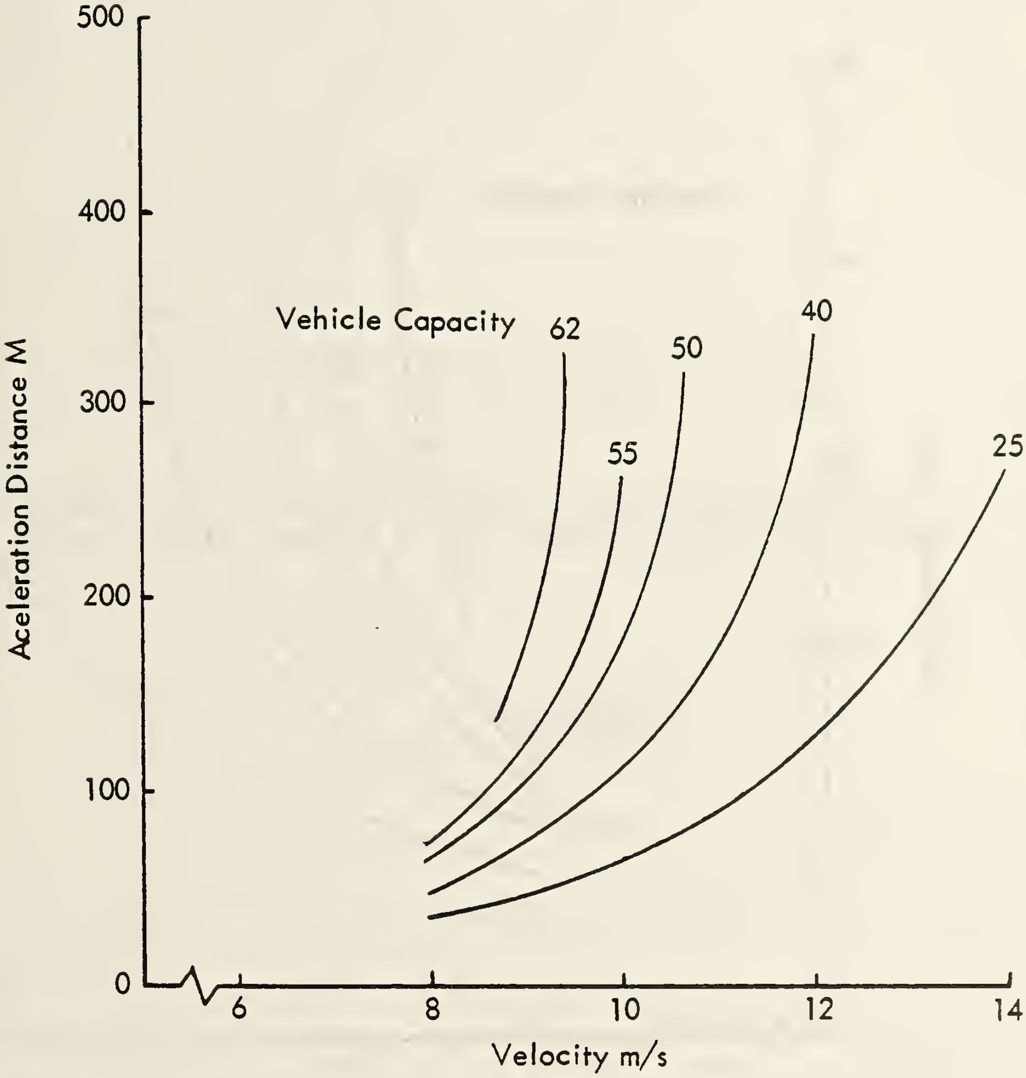


FIGURE B-8. ACCELERATION DISTANCE VERSUS VELOCITY FOR IGRT VEHICLES WITH 38-69% SEATS

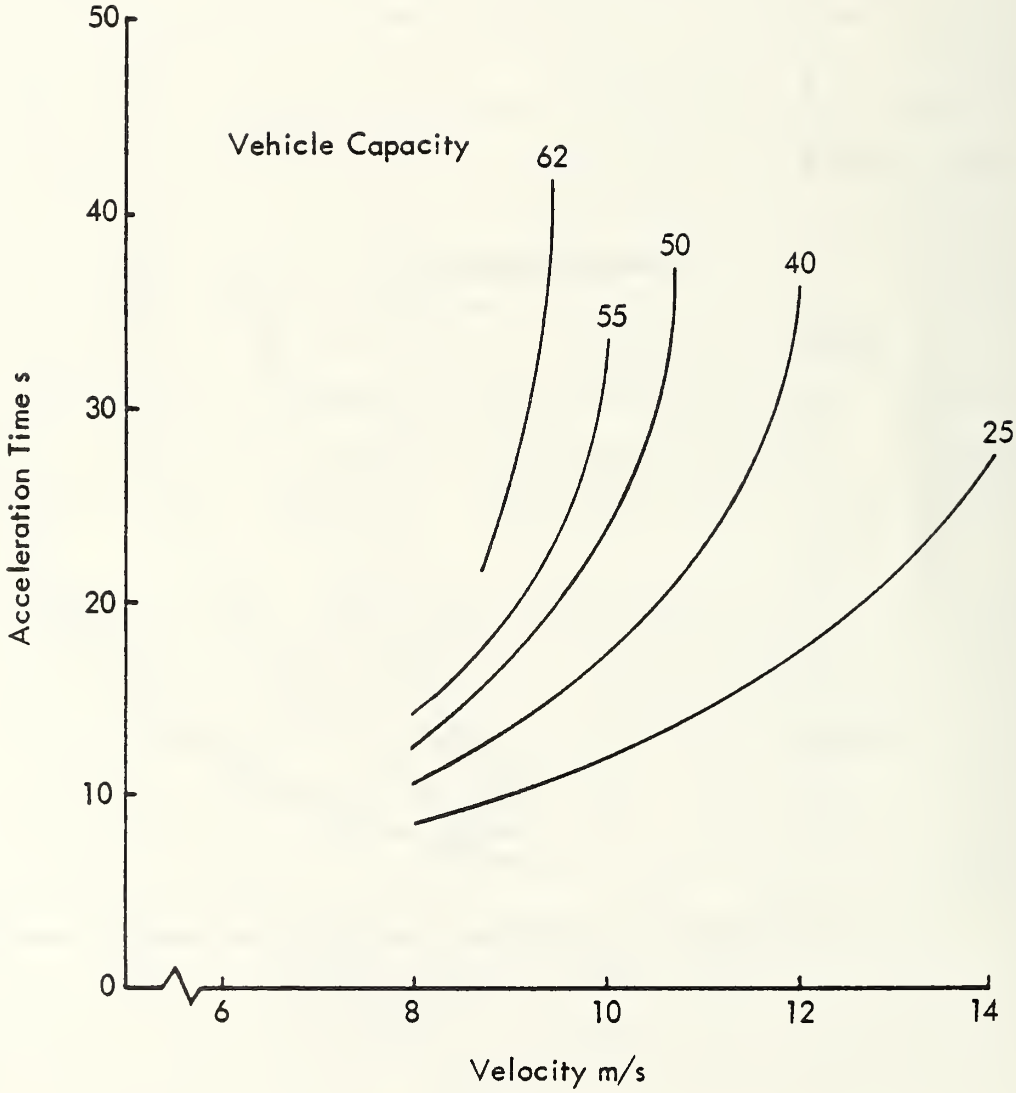


FIGURE B-9. ACCELERATION TIME VERSUS VELOCITY FOR 'GRT VEHICLES WITH 38-69% SEATS

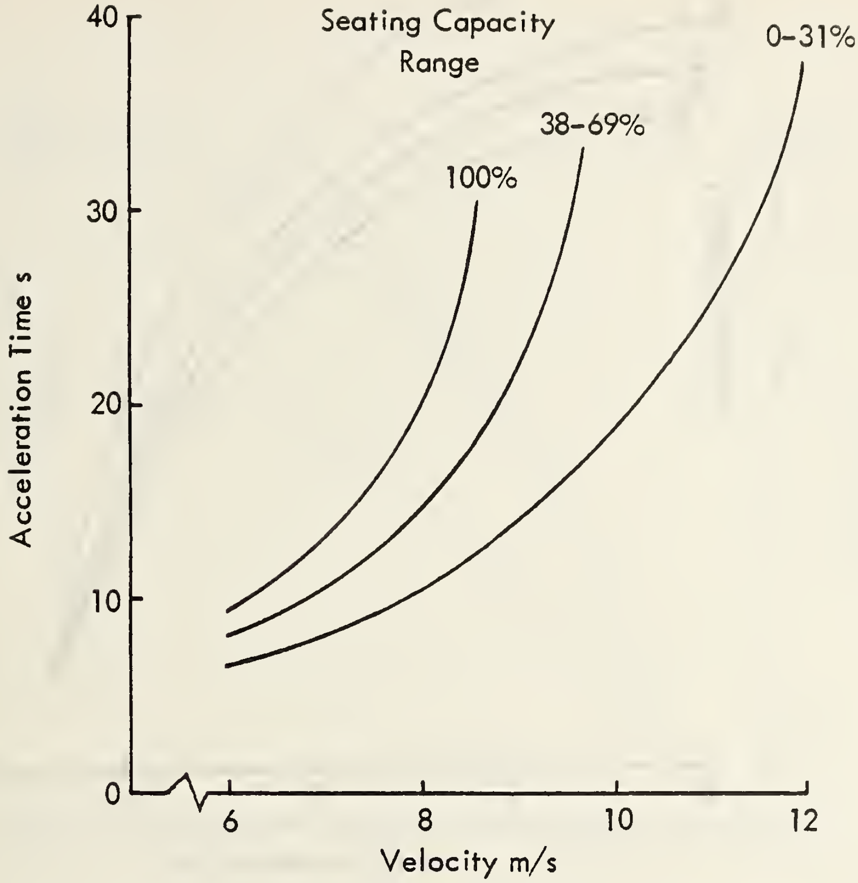


FIGURE B -10. ACCELERATION TIME VERSUS VELOCITY FOR 58-PASSENGER VEHICLES WITH DIFFERENT SEATING CAPACITIES

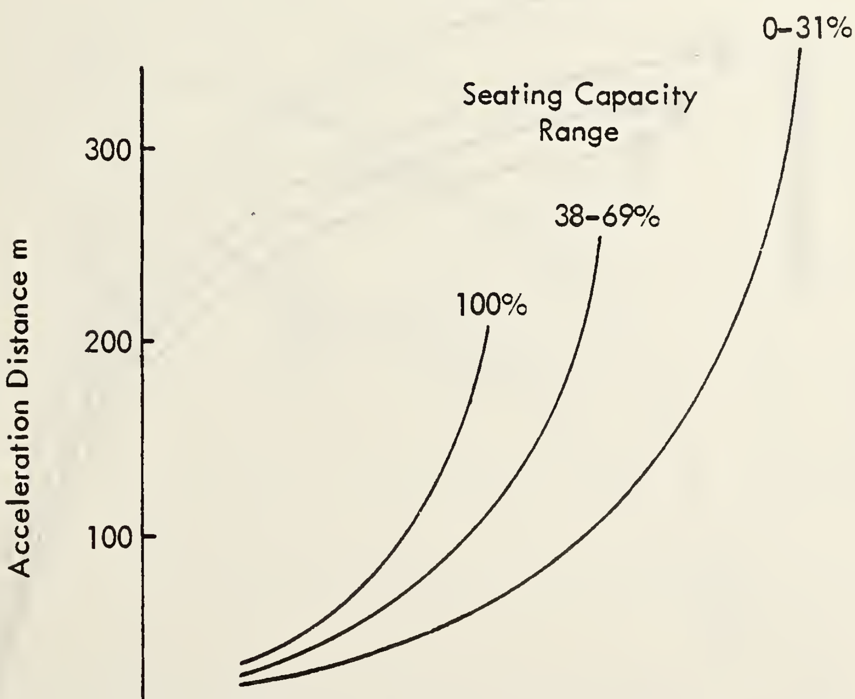


FIGURE B -11. ACCELERATION DISTANCE VERSUS VELOCITY FOR 58-PASSENGER VEHICLES WITH DIFFERENT SEATING CAPACITIES

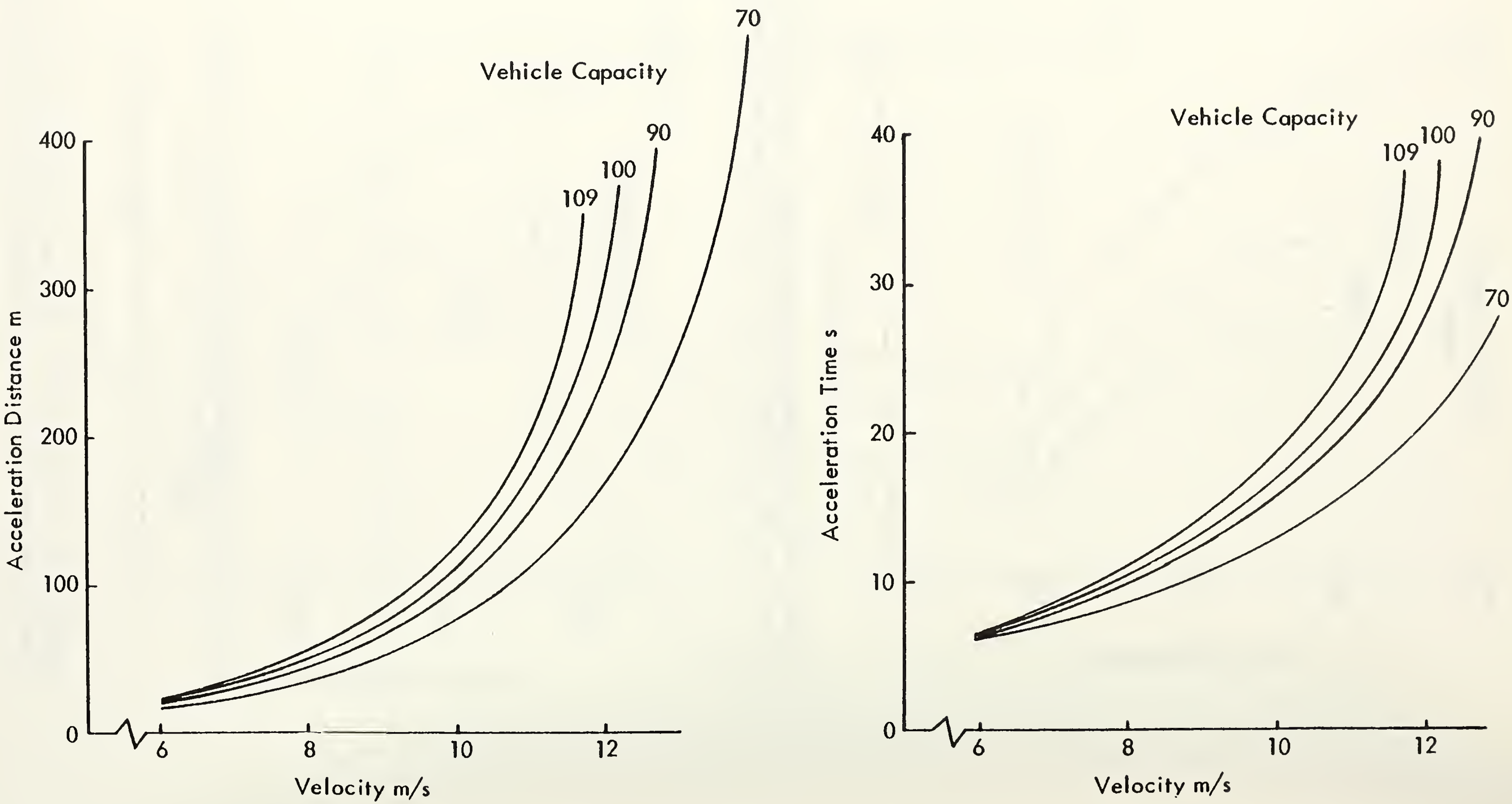
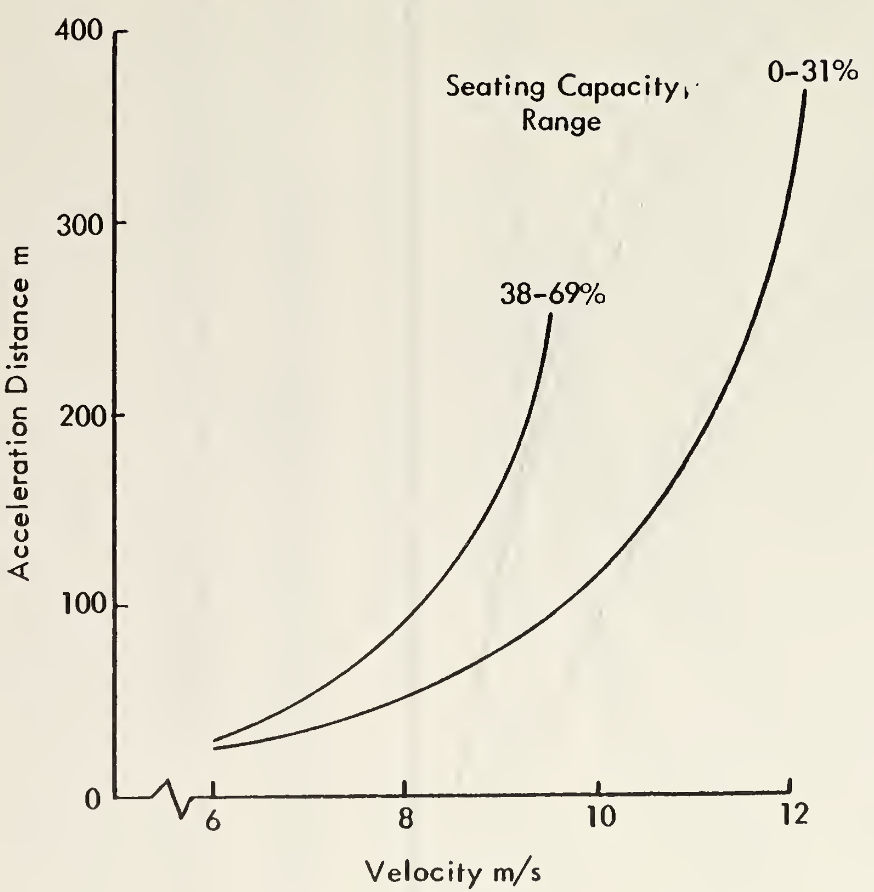


FIGURE B-12. ACCELERATION DISTANCE AND TIME VERSUS VELOCITY FOR LGRT VEHICLES WITH 0-31% SEATS



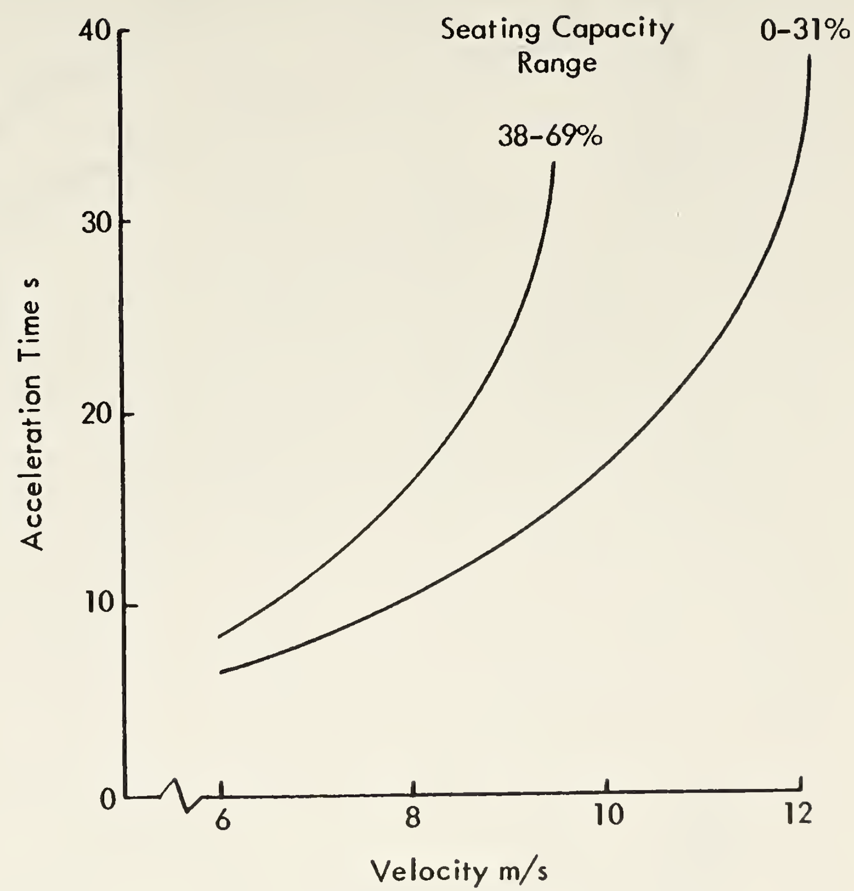


FIGURE B-13. ACCELERATION DISTANCE AND TIME VERSUS VELOCITY FOR 100-PASSENGER VEHICLES WITH DIFFERENT SEATING CAPACITIES

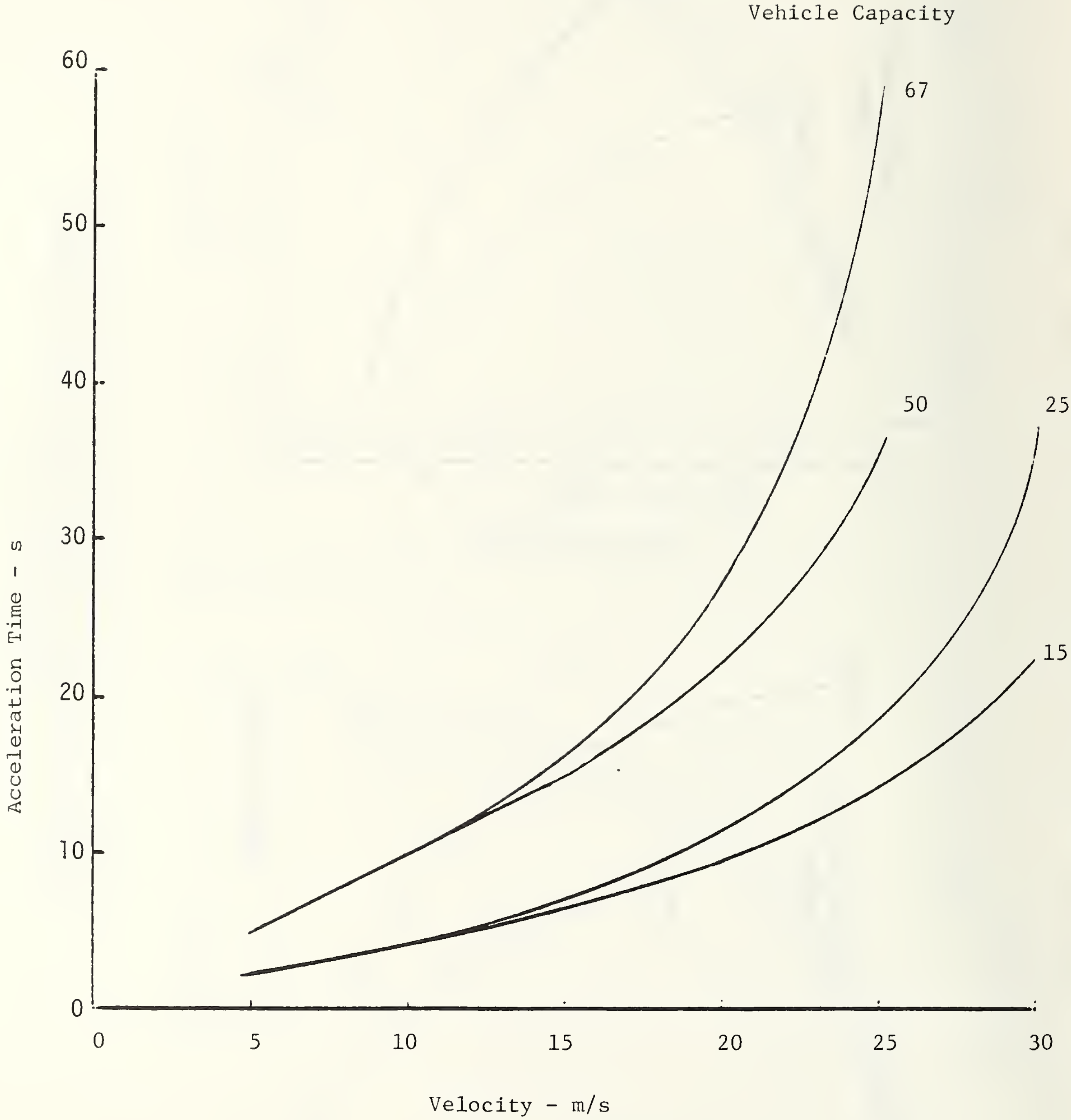


FIGURE B-14. ACCELERATION TIME versus VELOCITY FOR GRT VEHICLES

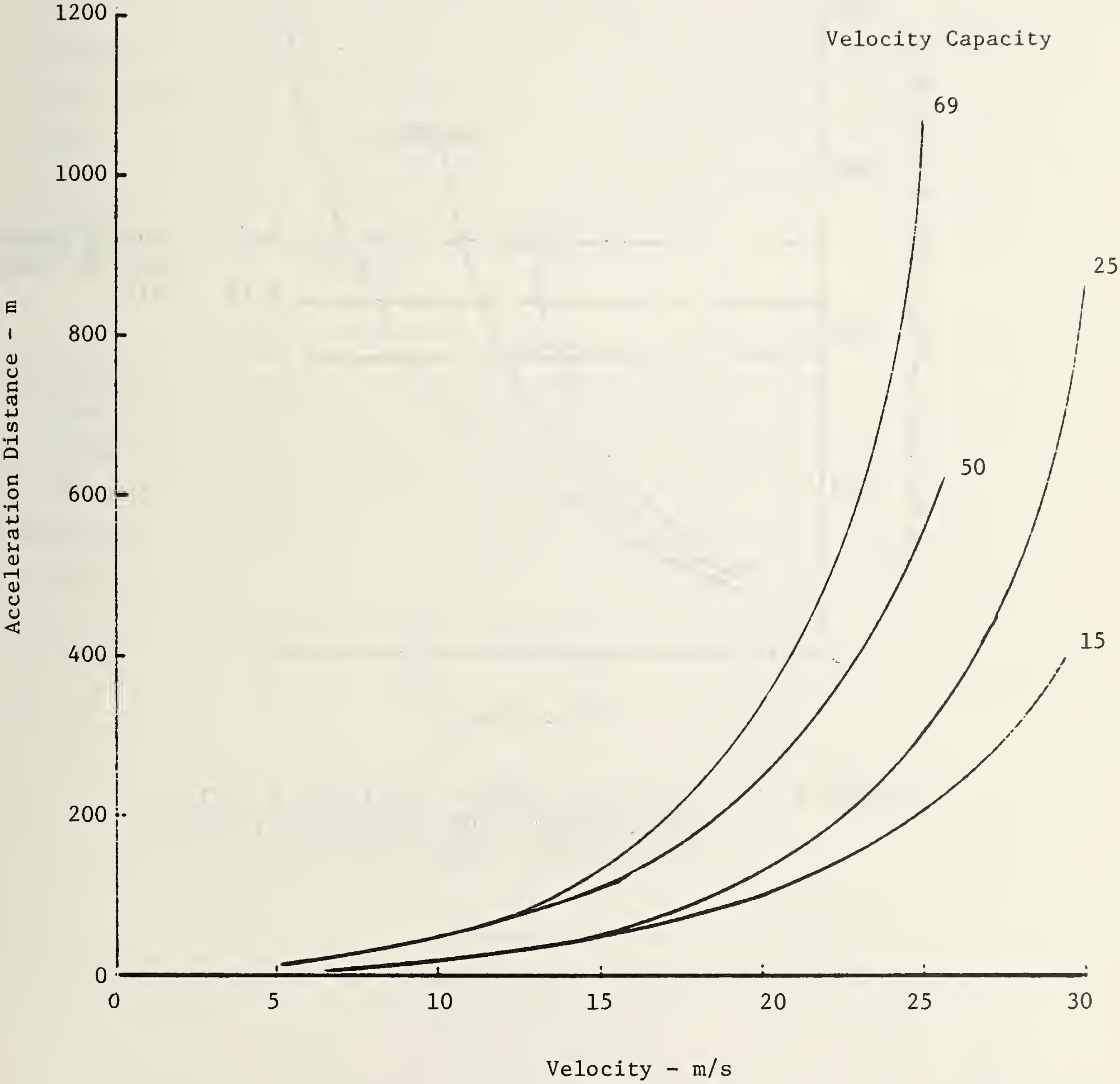


FIGURE B-15. ACCELERATION DISTANCE versus VELOCITY FOR GRT VEHICLES

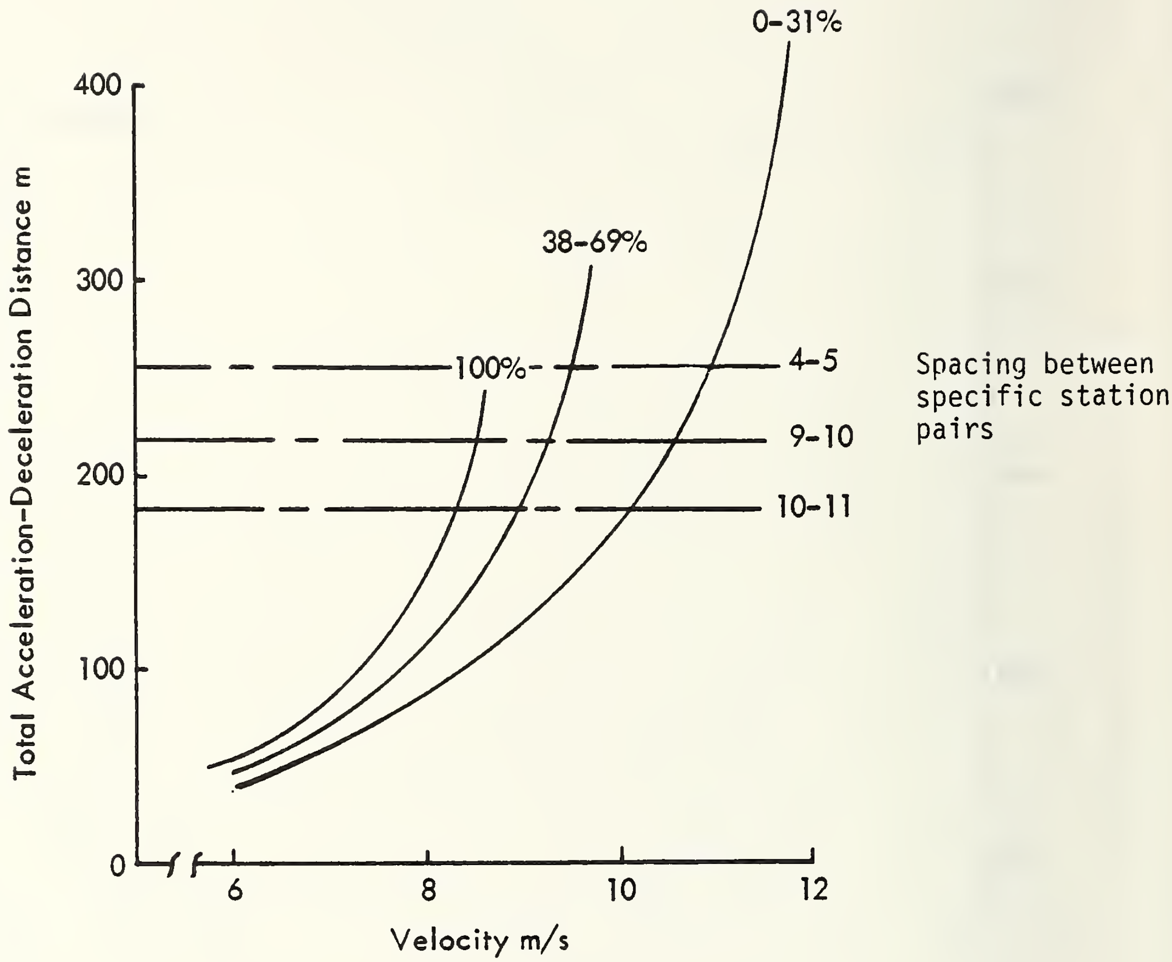


FIGURE B-16. TOTAL ACCELERATION - DECELERATION DISTANCE VERSUS VELOCITY FOR 58-PASSENGER VEHICLES WITH DIFFERENT SEATING CAPACITIES

The energy required for cruising at a constant velocity is simply the time integral of the road-load power equation, Equation B-2, with acceleration (a) equal to zero. The calculation of energy consumed during acceleration maneuvers from stations is complicated by the fact that acceleration varies with velocity and, therefore, with time. The equations used to calculate vehicle energy for acceleration and constant velocity cruise are derived in Section B.5 at the end of this appendix. Since the equations are complex, the use of a programmable calculator to aid in their evaluation is almost imperative.

Many of the same parameters that are used in establishing acceleration performance are required inputs to the energy consumption equations, but the values of several parameters are different. While the acceleration profile is determined for "worst-case" conditions of headwind, grade, and vehicle mass, energy consumption is calculated assuming average values for these parameters. The values of both headwind velocity and percent grade are assumed to be zero for the purpose of estimating energy consumption. When all vehicles are powered, trains have a slight performance advantage over individual vehicles because the frontal area of the train is the same as that of a single vehicle. However, the same acceleration profile that is used to estimate vehicle performance (i.e., the same values of a_m, V_1, a_f, and V_c) is used in the vehicle energy calculations. Traveling unit mass is taken as that of the train with an average passenger load for each major demand period (e.g., a.m. peak, p.m., peak, and off-peak). Since an entire demand period is usually not simulated, the average number of passengers per vehicle must be estimated based on results obtained by simulating a portion of the demand period. The estimate that is suggested for the purpose of calculating energy is the ratio of total passenger travel time to the total time that vehicles are in motion. Passenger travel time for a demand period is the mean passenger demand for the period as indicated by the appropriate demand matrix times the average travel time for trips completed during the simulation period. Vehicle travel time is the difference between total vehicle hours and the accumulated dwell time for all vehicles during the demand period. The value of average passengers per vehicle is somewhat overestimated for deployments in which passengers must transfer because the transfer time is included in the average travel time statistic generated by the Discrete Event Simulation Model (DESM). This is

not a serious error because vehicle propulsive energy is not highly sensitive to the number of passengers per vehicle as illustrated in Figure B-17. This plot of propulsive energy versus vehicle occupancy for a 100-passenger LGRT vehicle indicates that an estimate of 60 passengers per vehicle in a situation where actual vehicle occupancy may be only 50 passengers (a 20 percent overestimation) results in overestimation of acceleration and cruise energy requirements of 5.7 percent and 4.1 percent, respectively. If propulsive energy represents 50 percent of total vehicle energy requirements, then the error is reduced to only 2 to 3 percent of total vehicle energy.

The value of propulsive energy which is calculated from consideration of the equations of motion corresponds to that consumed at the guideway-vehicle interface. Propulsion efficiencies must be considered to relate the calculated value to the energy which must be generated to support vehicle operation. The propulsion efficiencies considered in the SOS analyses include those of a controller (95 percent), a motor (90 percent), and a drive train (90 percent). These assumptions result in an overall propulsion efficiency of 77 percent.

Figure B-18 is an example of a form used in the SOS analyses to calculate vehicle propulsive energy for a particular demand period. This example illustrates the calculation of vehicle propulsive energy for an SLT deployment in the noon peak 3-hour period. Vehicle and train parameters are recorded at the top of the form for reference. The average number of passengers per vehicle is calculated using the data and procedure indicated at the bottom of the form. The propulsive power constants (C_1, C_2, and C_3) are calculated using Equations B-3, B-4, and B-5 as described in this appendix. The acceleration energy per acceleration and cruise energy per kilometer are calculated using the equations presented in Section B.5. The number of accelerations used in the calculation of acceleration energy can be estimated as the number of station stops by trains as determined from system simulation. The number of train kilometers traveled on the mainline guideway at cruise velocity can also be determined from the simulation output. However, the techniques used to model the network, as described in Section 3.0, must be considered in the interpretation of the simulation

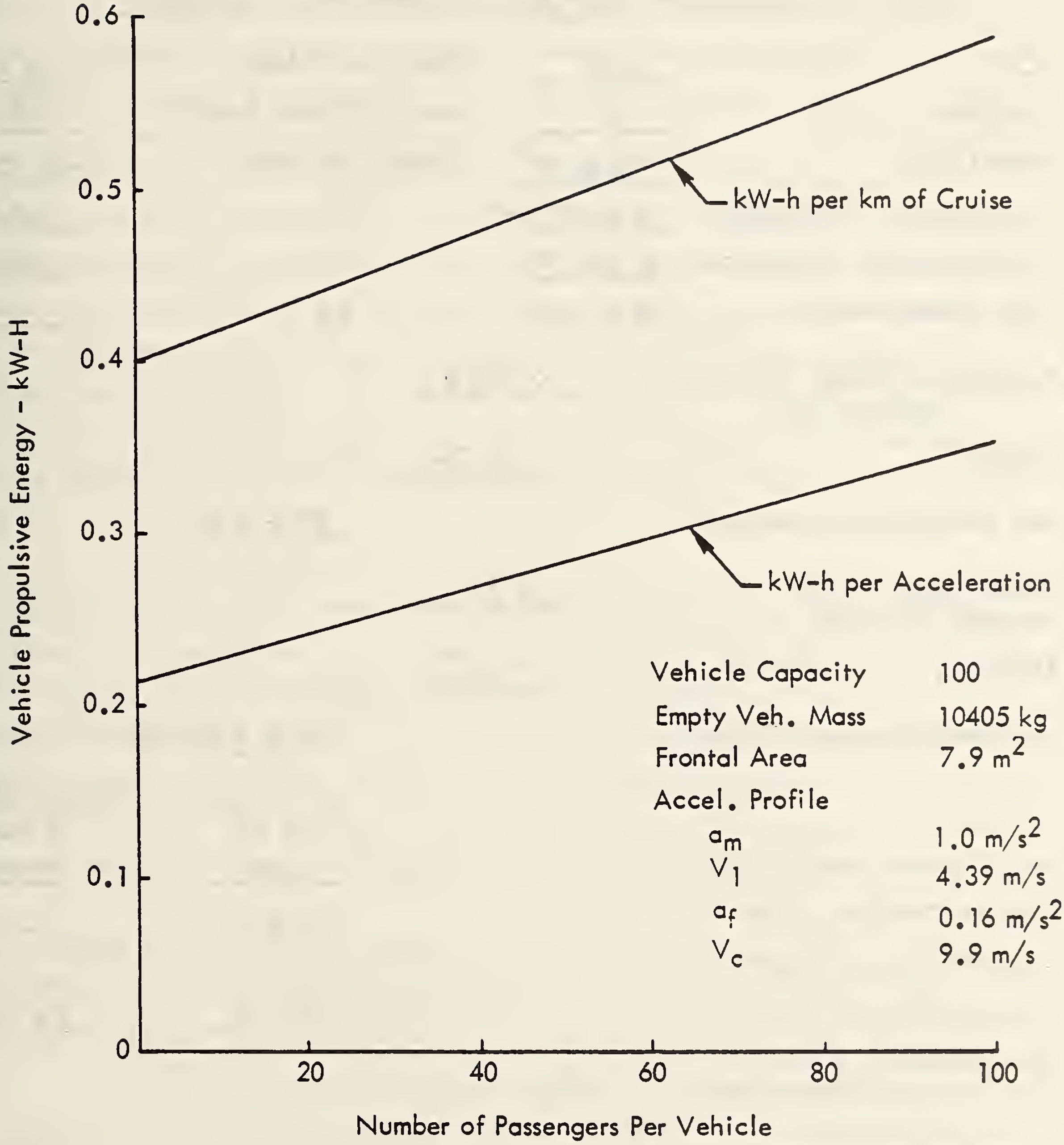


Figure B-17. VEHICLE PROPULSIVE ENERGY VERSUS NUMBER OF PASSENGERS PER VEHICLE

Deployment SLT 4 Demand Period PEAK

VCAP	62	Empty Veh. Mass	11 837 kg
Cars/Train	2	Avg. No. Pass./Veh.[1]	38.8
Frontal Area	4.82 m^2	Loaded Train Mass	28 953 kg
a_f (Single Veh., Worst Case)	0.090 m/s^2	C_1	1158.1
V_1 (Single Veh., Worst Case)	2.95 m/s	C_2	108.57
Avg. Cruise Velocity	8.0 m/s	C_3	1.887

Acceleration Energy Per Accel. (Register 16)	0.303	
Efficiency	77%	
Net Energy Per Acceleration		.394 kWh
Cruise Energy Per km (Register 17 * 1000)	0.597	
Efficiency	77%	
Net Energy Per km of Cruise		.775 kWh/km

	Sim. Period 1.5 h	Demand Period 3.0 h
No. of Station Stops by Trains	738	1476
Train km Traveled (Gross)	222.2	
Total Station Link Length	121.9	
Train km at Cruise Velocity	132.2	264.4 km

Job Reference - Z (3673)
6 2-CAR TRAINS/LANE

Energy for Acceleration	581.1
Energy for Cruise	204.8
Total Energy	785.9 kWh

---

[1]A. Total Demand/Period 29,225
B. Avg. Travel Time 187.4 s
C. No. Stn. Stops by Veh./Period 2952
D. Avg. Dwell Time 40 s
E. No. of Veh. 24
F. No. Sec./Period 10,800

Avg. No. Pass/Veh. = $\frac{A * B}{E*F - C*D}$

FIGURE B-18. CALCULATION OF PROPULSIVE ENERGY CONSUMPTION

results. For example, if the suggestions given in Section 3.0 for modeling networks with on-line stations are followed, then the DESM output statistic, vehicle kilometers traveled, includes distance traveled during acceleration/deceleration maneuvers as well as distance traveled at cruise velocity. Therefore, to estimate the number of train kilometers traveled at cruise velocity, the distance traveled on station acceleration and deceleration ramps (product of station link length and number of station entries by trains) is subtracted from the total train kilometer value. The total energy consumed during accelerations from stations is the product of net energy per acceleration and the number of accelerations (number of station stops by trains). Similarly, the total energy required for cruise equals the product of net energy per kilometer of cruise and the number of train-kilometers traveled at cruise velocity (distance traveled on guideway links).

Vehicle energy requirements for auxiliaries such as lights, electronic equipment, air conditioning, and heating represent a significant portion of total vehicle energy requirements. Estimates of auxiliary energy consumption per vehicle hour of operation are presented for the vehicle types that were considered in the System Operations Studies. The estimates, which are derived from previous studies and actual experience, are intended to serve as guidelines in studies where more detailed data are not available.

Lighting and control requirements represent a large portion of the energy required for on-board vehicle auxiliaries in AGT vehicles. In a study of auxiliary power requirements for the 17-passenger GM Dual Mode Vehicle concept[33], the average energy required for lights, warning devices, etc. was estimated to be 2.9 kWh for each vehicle operating hour. At the other end of the vehicle size spectrum, the MARTA specification identifies an auxiliary load for purposes other than heating and cooling of 33.7 kW.[34] Of this, 26.8 kW are required continuously, and the remaining 6.9 kW are required intermittently. Assuming the intermittent power is required 50 percent of the time, the lighting and control energy load for the 140 passenger MARTA vehicle is 30.3 kWh per vehicle hour. As a first approximation, it is assumed that the auxiliary energy requirements for vehicle lighting and control vary linearly with vehicle capacity. The straight line defined by these two points is shown in Figure B-19.

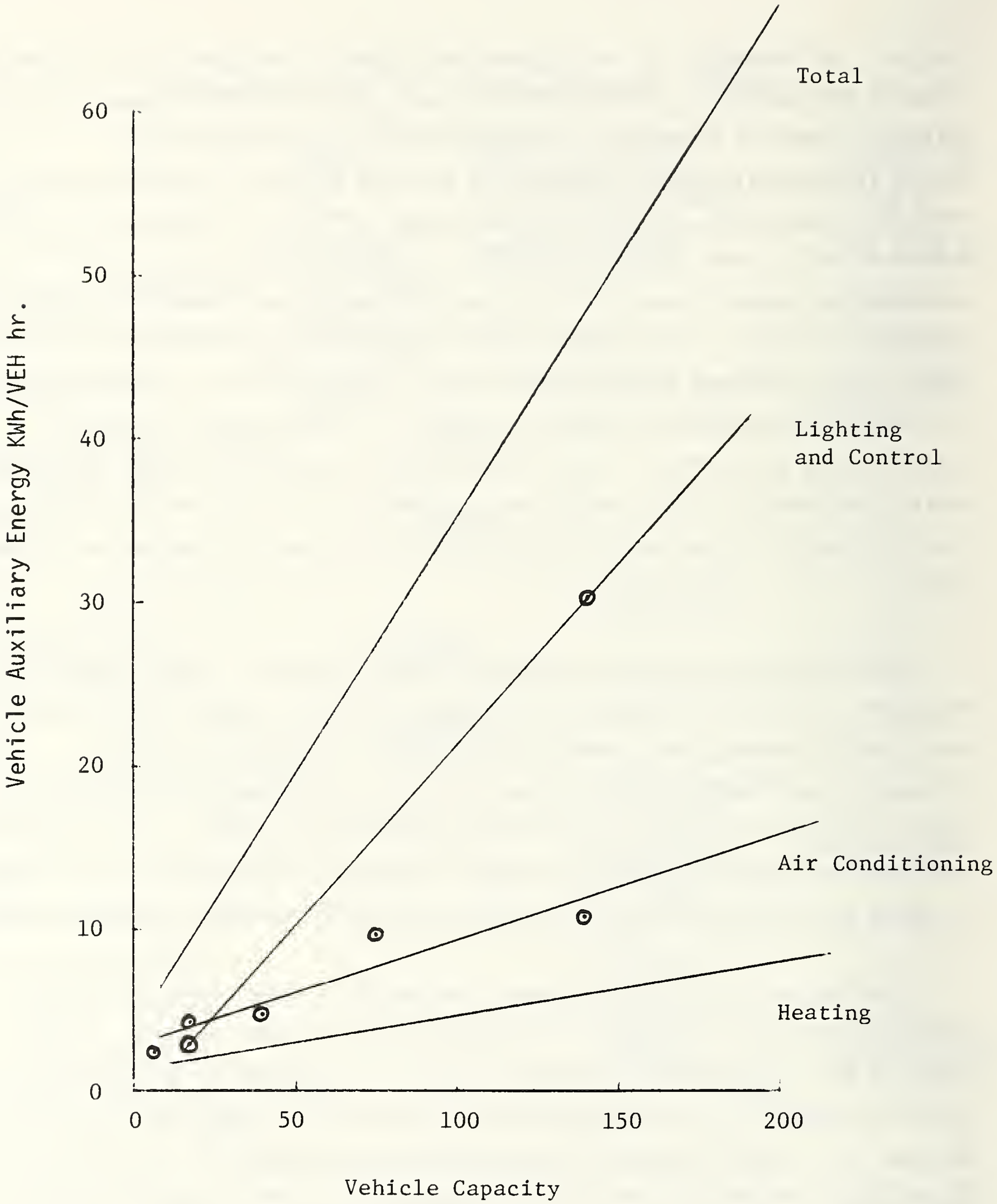


FIGURE B-19. VEHICLE AUXILIARY ENERGY CONSUMPTION

Air conditioning represents a second major category of auxiliary energy consumption. Vehicle air conditioning energy requirements were estimated based on reported power requirements for AGT vehicles and the assumption that air conditioning is required 35 percent of the time. While this assumption is arbitrary, it can be interpreted as a 70 percent use factor during the warmer half of the year. The results which are based on this assumption can be scaled linearly if a different use factor is assumed. The air conditioning load for the 17-passenger GM Dual Mode Vehicle was estimated as 12.1 kW or 4.2 kWh per vehicle hour assuming the 35 percent duty cycle. A 40-foot GMC transit coach has a 10-ton air conditioning unit which requires 37 hp (27.6 kW) to drive the compressor. Assuming that the air conditioner is operated 35 percent of the time, the energy consumption is 9.7 kWh per vehicle operating hour. The energy efficiency ratio (EER) for this unit is

$$\frac{10 \text{ ton} \times 12{,}000 \text{ BTU/h/ton}}{27{,}600 \text{ W}} = 4.35$$

A typical automobile is equipped with a 2.5 ton air conditioner. Assuming the same EER rating (4.35), this unit requires 6.9 kW (9.25 hp) to drive the compressor. With a 35 percent use factor, this becomes 2.4 kWh per vehicle hour. According to the AIRTRANS Assessment report[35], two 25-ton air conditioners are used on each 40-passenger vehicle. With an EER rating of 4.35, these units require 14 kW to drive the compressor. Using a 35 percent use factor for consistency, this becomes 4.9 kWh per vehicle hour. The MARTA specification[34] gives an estimate that 31 kW are required to cool each 140-passenger vehicle. Assuming the 35 percent use factor, the estimated energy requirements for air conditioning the MARTA vehicles is 10.9 kWh per vehicle hour. The estimated air conditioning energy requirements for these five vehicles are plotted against vehicle capacity in Figure B-19. A least squares line through these points (Y = 0.064 X + 2.85 where X is vehicle capacity) is also shown.

A third major use of auxiliary energy onboard electric AGT vehicles is for heating the passenger compartment in cold weather. If the vehicle is exposed to the elements and operates with frequent stops to load and unload passengers, then heating loads can be significant. The heating load for the MARTA vehicles is estimated to be 15kW[34] -- or nearly 50 percent of the air

conditioning load. As a first approximation, therefore, it is assumed that the energy requirement for heating is one-half the requirement for air conditioning.

The total rate of auxiliary energy consumption estimated for AGT vehicles is shown as a function of vehicle capacity in Figure B-19. The total value is the sum of the estimates for lighting and control, air conditioning, and heating. The assumptions which are implicit in these estimates are as follows:

1. Cooling of the passenger compartment is required during 35 percent of the annual vehicle operating hours
2. Requirements for heating, cooling, lighting, and control increase linearly with vehicle capacity.

In a comparative study of several systems representing different classes of AGT systems, it may be convenient to select a characteristic value of auxiliary energy for each class. This simpler approach was used in the System Operations Studies. Table B-10 gives total and component energy consumption values for a selected vehicle in each system class.

TABLE B-10. AUXILIARY ENERGY REQUIREMENTS FOR REPRESENTATIVE AGT VEHICLES

System Class	Ref. Veh. Capacity	Lighting & Control kWh/Veh L	Air Conditioning kWh/Veh h	Heating kWh/Veh L	Total kWh/Veh h
PRT	6	0.45	3.24	1.62	5.31
SGRT	15	2.45	3.81	1.91	8.17
IGRT	40	8.02	5.42	2.71	16.15
LGRT	100	21.39	9.27	4.63	35.29
ART	190	41.44	15.04	7.52	64.0

B.4 VEHICLE NOISE GENERATION

The effect of noise generated by an AGT system on the surrounding community can be measured in terms of the area adjacent to the guideway within which the day-night sound level resulting from the operation of AGT vehicles is greater than 55 dbA. This level has been selected by the Environmental Protection Agency to represent the level of noise which causes annoyance and interference with outdoor activities.

The day-night sound level is defined as the equivalent A-weighted sound level for an entire service day (up to 24 hours) with a 10 dbA weighting applied to the equivalent sound level during the nighttime hours of 10:00 p.m. to 7:00 a.m. This noise measure is defined in terms of system parameters in Appendix C of the Measures of AGT System Effectiveness report.[36] The defining equation presented in Reference 36 can be expressed in the following form:

$$L_{dn} = 10 \log \left[\sum_{i} \frac{Ti}{24} \quad \frac{K}{R(1 + R/\ .3i)} \right] \qquad \text{(B-15)}$$

where

L_{dn} = Day-night noise intensity

Ti = Effective time when a train of length i cars is passing the observation point on the guideway section under consideration (includes the nighttime weighting)

R = Number of vehicle lengths from the guideway at which the day-night noise intensity equals 55 dBA

i = Number of cars per train

The constant, K, is chosen to satisfy the following relationship:

$$L = 10 \log \left[\frac{K}{R' \ (1 + R'/.3i)} \right] \qquad \text{(B-16)}$$

where L = Exterior noise value for the vehicle or train under consideration in dbA

R' = Number of vehicle lengths from the guideway at which the given exterior noise level was measured

The noise impacted area, the measure of noise used in the System Operations Studies, is the land area within which the day-night noise intensity (L_{dn}) is greater than 55 dbA. This value is the product of guideway length and twice the distance from the guideway at which L_{dn} equals 55 dbA. This distance can be determined by solving Equation B-15 for R after the value of K has been determined from Equation B-16. The calculation of the noise impacted area for a section of guideway is greatly simplified if one of two assumptions is valid. If one of the terms in Equation B-15 is much greater than the others, then the day-night noise intensity can be expressed as follows:

$$L_{dn} = 10 \log \left(\frac{Ti}{24}\right) + 10 \log \left[\frac{K}{R(1 + R/ .3i)}\right] \qquad \text{(B-17)}$$

If the level of noise generated by the AGT system is relatively low so that the value of R at which L_{dn} is less than 55 dbA is small (less than 0.3i), then Equation B-15 can be simplified to the following form:

$$L_{dn} = 10 \log \left[\sum_i \frac{Ti}{24}\right] + 10 \log \left(\frac{K}{R}\right) \qquad \text{(B-18)}$$

Use of these simplifying assumptions permits the use of a simple graphic technique to determine the value of R (half-width of the noise impacted area expressed in vehicle lengths).

The technique used to calculate the noise measure during the System Operations Studies is best described by example. The first step is to establish the exterior noise characteristic of the vehicle under consideration.

Table B-11 lists noise data for several AGT vehicles based on information tabulated in the SOS report Classification and Definition of AGT Systems.[23] The reference noise levels are measured at a variety of distances from the vehicle. To permit comparison of these values, the data were normalized to a common measurement distance of 7.6 m (25 ft.). The normalization was accomplished using a plot of sound level versus normalized

TABLE B-11. EXTERIOR NOISE CHARACTERISTICS OF AGT VEHICLES

System Class	System Name	Reference Exterior Noise	Normalized Exterior Noise	Selected Value
Low Speed PRT				66dbA at 7.6m
	Cabinentaxi	60-65dbA at 7.5m	62dbA at 7.6m	
	Aramis	70dbA at 7.5m	70dbA at 7.6m	
	Aerial Transit System	63dbA		
High Speed PRT				68dbA at 7.6m
	CVS	NCA 50 at 10m*	53dbA at 7.6m	
	Monocab	70dbA at 15.2m	82dbA at 7.6m	
Low Speed SGRT				69dbA at 7.6m
	Morgantown	NCA 60 at 7.6m*	60dbA at 7.6m	
	Ford ACT	78dbA at 7.6m	78dbA at 7.6m	
High Speed SGRT				70dbA at 7.6m
	GEC Minitram	70dbA at 7.5m	70dbA at 7.6m	
	GM DMTS	82dbA		
	Rohr DMTS	90dbA at 7.6m	90dbA at 7.6m	
	TTD DMTS	70dbA at 7.6m	70dbA at 7.6m	
Low Speed IGRT				72dbA at 7.6m
High Speed IGRT				74dbA at 7.6m
	Dashaveyor I	72dbA at 7.6m	72dbA at 7.6m	
	KCV	67dbA at 6.0m	70dbA at 7.6m	
	Kompactbahn	80dbA at 5.0m	85dbA at 7.6m	
	MAT	64dbA at 30.0m	80dbA at 7.6m	
	Mini-monorail	75dbA at 10.0m	78dbA at 7.6m	
	NTS	60dbA at 7.5m	60dbA at 7.6m	
	Transurban	60dbA at 10.0m	63dbA at 7.6m	
	Tridim Aerotran	70dbA at 7.5m	70dbA at 7.6m	
	URBA-30	70dbA at 7.0m	69dbA at 7.6m	
	VONA	65dbA at 8.0m	66dbA at 7.6m	
LGRT				76dbA at 7.6m
	Westinghouse	NCA 60 at 30.5m*	76dbA at 7.6m	
ART				88dbA at 7.6m
	BART	74dbA		
	Rohr N Series	NCA 60 at 30.5m*	76dbA at 7.6m	
	VAL	70dbA at 60.0m	94dbA at 7.6m	
	WMATA	84dbA at 15.0m	93dbA at 7.6m	

* Differences between the NCA and dbA scales are assumed to be negligible for this analysis.

measurement distance such as the one presented in Figure B-20. The slopes of the lines in this plot are constant, but the scale of the ordinate is defined by the value of external noise of the vehicle under consideration. The intersection of the line defined by 10 log (K/R) with the line defined by $10 \log \frac{K}{R(1+R/3i)}$ occurs at a measurement distance of 0.3 vehicle lengths for single vehicles (i=1). The proper scale of the ordinate was determined for each vehicle listed in Table B-11, and the sound level corresponding to 7.6 m was determined from the graph. In this analysis, differences between the NCA and dbA scales are assumed to be negligible. The table lists a default value of external vehicle noise for each system class. In most cases the selected value is the average of the normalized values measured at 7.6 m. The values increase with vehicle size, and the high speed vehicles are somewhat more noisy than low speed vehicles of the same size class. The lower value rather than the average was selected for the High Speed SGRT class because more confidence is placed on the GEC value which is based on test track operations than on the others which are based on conceptual designs. No data were found to define the exterior noise characteristics of Low Speed IGRT systems. The selected value is approximately midway between the values selected for Low Speed SGRT and Low Speed LGRT, and it is less than the value selected for High Speed IGRT systems. The value selected for the High Speed IGRT system class is the average of the eight highest values listed for that class in Table B-11. The two lowest values (NTS - 60 dbA at 7.6 m and Transurban - 63 dbA at 7.6 m) were considered to be unrepresentative of the class.

The second step in the procedure is to compute the values of effective time (Ti) for sections of the network. Guideway links having identical vehicle flows and train consists for the same time periods during the day can be considered as a section. The number of different guideway sections which are considered should be as small as possible to simplify the calculation. Simple loop or shuttle networks can generally be considered as a single section. In branch or simple grid networks where different numbers of vehicles or consists operate on different routes, several different sections must often be considered. In more complex grid networks, it is sometimes sufficiently accurate to assume uniform flow throughout the

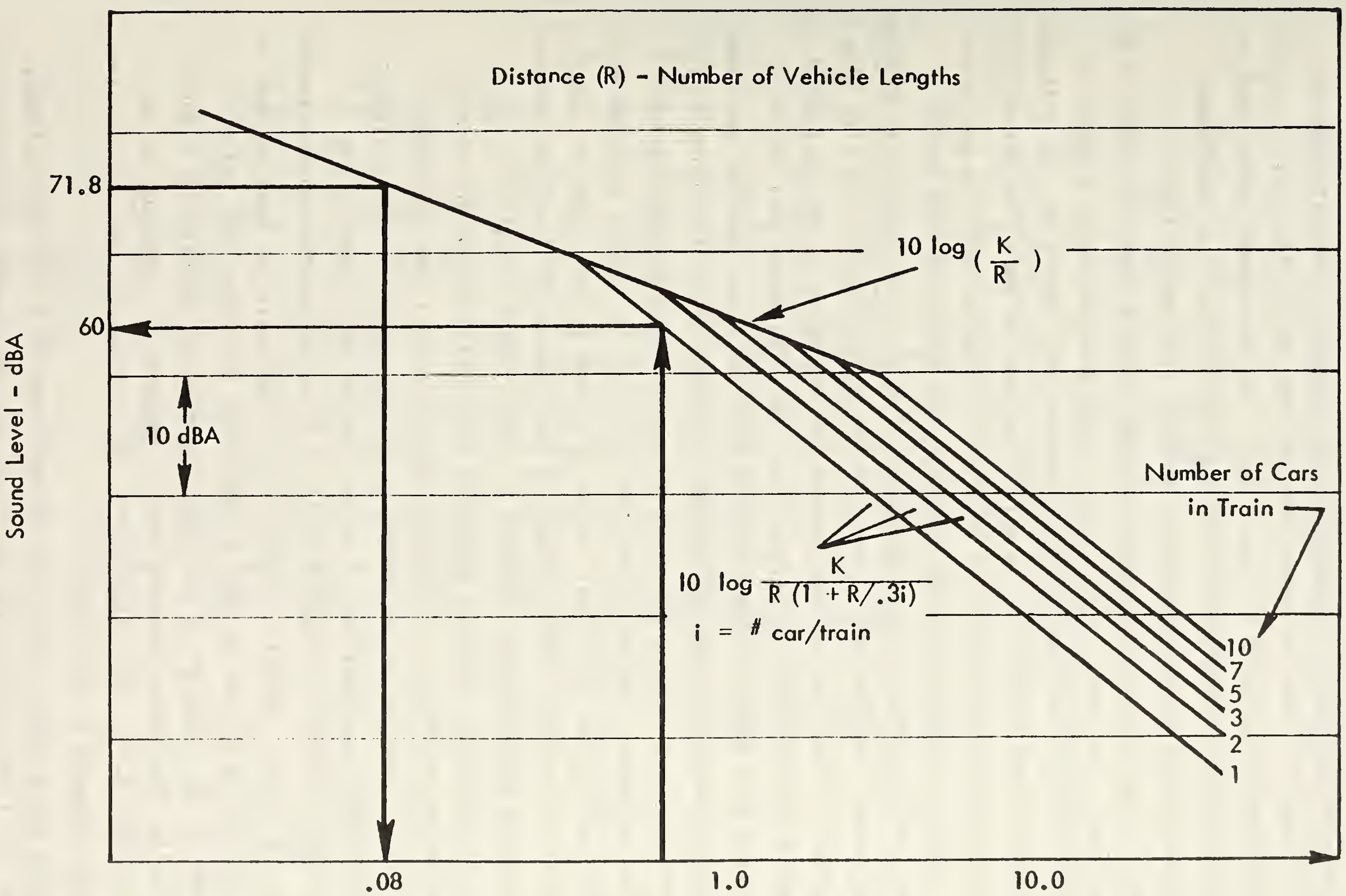


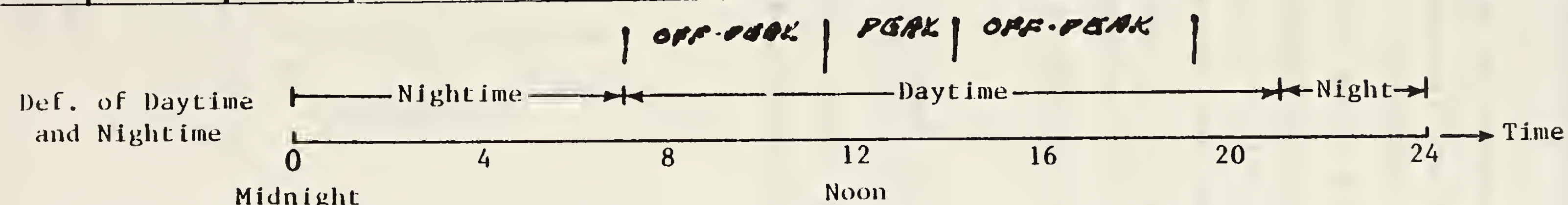
FIGURE B-20. SOUND LEVEL VERSUS DISTANCE FOR VARIOUS LENGTH TRAINS

network for the purpose of estimating noise impacts. Computation of the effective times (Ti) and the noise impacted area can be facilitated by the use of the form illustrated in Figure B-21. The form shows values used to calculate the noise impacted area for an eleven-station loop deployment analyzed during the System Operations Studies. The entire loop is considered in the calculation because average vehicle flows are equal on all guideway links. The table at the top of the figure serves as a guide in computing the effective times (Ti) in Equations B-17 and B-18. As indicated in the table column labeled 6, the effective time for each time period of different active fleet size is the product of number of vehicles per train, average number of vehicles on the guideway, and operating time where nighttime operating hours are weighted by a factor of 10 relative to daytime operating hours. Daytime and nighttime hours are defined by the time line in the center of the figure. The assumed service hours of the deployment in this example are indicated above the time line. The lower part of the figure serves as a guide in computing the value of noise impacted area once the effective times have been determined. Equation B-18, the approximation to day-night noise intensity for small values of R, is repeated in the figure for reference. As indicated, the values of Ti in this equation are obtained by adding the individual values in column 6 calculated for equal values of train consist. After computing the value of 10 log (K/R), Figure B-20 is used to determine the value of R. This figure illustrates the geometric attentuation of sound intensity with distance from the source. The scale of the ordinate is 10 dbA per major division, but the origin depends on the intensity of the source (i.e., the exterior noise level of the vehicle under consideration). In the case of this example, the reference for calibrating Figure B-20 is an exterior vehicle noise value of 60 dbA at 7.6 m (.627 vehicle lengths). Once the scale has been defined in this manner, the graph can be used to determine the value of R which corresponds to the value of 10 log (K/R) computed as indicated in Figure B-21. Finally, the noise impacted area is computed as indicated at the bottom of Figure B-21. The value of R is doubled because the area on each side of the guideway is impacted.

In cases where equal flows occur on each lane of a dual-lane guideway, the values of Ti are computed for each lane and then summed as indicated in the calculation procedure.

Deployment SLT 3 Guideway Section ENTIRE LOOP

Time Period		Veh./ Train (1)	Veh. Length/ Guideway Length (2)	Ave. Number of Veh. on Guideway (3)	Daytime Hours (4)	Nighttime Hours (5)	Effective Time for Fleet (6)=(2)×(3)×(4)+10×(5)
PEAK	18	2	.00328	18	3	0	.177
OFF-PEAK	11	1	.00328	11	9	0	.324



Vehicle Length 12.12 m
Guideway Lane Kilometres 3.7 km
Exterior Vehicle Noise 60 dBA at 7.6 m
at .627 vehicle lengths

Ti = $\sum$(6) for fleets of i vehicles per train

$$\text{Ldn} = 10 \log \sum_i \frac{Ti}{24} + 10 \log K/R \quad \text{(small R approximation)}$$

$$55 - 10 \log \sum_i \frac{Ti}{24} = 10 \log K/R$$

$$55 - 10 \log \left(\frac{.501}{24}\right) = 71.8$$

R = .08 (from plot)

N/A = 2 * R * (Vehicle Length) * (Guideway Lane Length)
2 * .08 * 12.12 * 3700 m
N/A = 7.18×10^3 m^2

FIGURE B-21. CALCULATION OF NOISE IMPACTED AREA (NIA)

B.5 DERIVATION OF VEHICLE ENERGY CONSUMPTION EQUATIONS

A portion of the vehicle analysis task is to determine the vehicle energy consumption characteristics for vehicle acceleration and cruise maneuvers. It is assumed that energy consumption during the deceleration maneuver is negligible, and this measure is not considered here. The energy analysis results are expressed in a form which permits determination of energy utilization as a function of loaded vehicle mass and cruise velocity. This appendix presents closed form expressions for energy usage per maneuver in terms of parametric constraints and specified dependent variables. Many of the symbols used in the development and in the presentation of the energy equations are defined in Section B.2 of this appendix.

B.5.1 ENERGY CONSUMPTION PER ACCELERATION MANEUVER

The acceleration profile to be used in the vehicle analysis task is shown in Figure B-22 together with the parameters defining this figure.

a_m = acceleration limit

a_f = terminal acceleration

V_c = cruise velocity

V_1 = maximum velocity subject at which the maximum acceleration (A_m) can be maintained

V_o = initial velocity

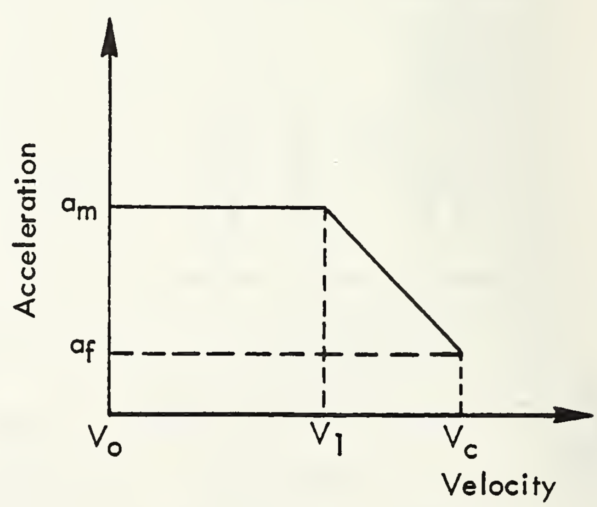


FIGURE B-22. ACCELERATION VERSUS VELOCITY PROFILE

For the vehicle acceleration maneuver, there are three cases of interest which depend on the initial vehicle state (V_o) and the desired vehicle cruise velocity (V_c) subject to the above profile. These cases are listed below followed by the development of generalized energy expressions for use in each case.

CASE I $\quad V_o \leq V_c \leq V_1 \qquad \text{Energy} = E_1 (V_o, v) \Big|_{v = V_c} \quad [J] \qquad$ (B-19)

CASE II $\quad V_o \leq V_1 \leq V_c \qquad \text{Energy} = E_1 (V_o, v) \Big|_{v = V_1} + E_2 (V_1, V_c) \quad [J] \qquad$ (B-20)

CASE III $\quad V_1 \leq V_o \leq V_c \qquad \text{Energy} = E_2 (V_1, V_c) \Big|_{V_1 = V_o} \quad [J] \qquad$ (B-21)

The energy required from a propulsion system to effect vehicle acceleration and cruise maneuvers is given by the integral

$$\text{Energy} = \int_{t_o}^{t_f} P \, dt = \int_{V_o}^{v} \frac{P(v)}{a(v)} \, dv \quad [J] \qquad \text{(B-22)}$$

where P = propulsive power

$a(v)$ = acceleration

The output propulsive power is equal to the sum of the power losses due to drag forces (P_L) and the power required for acceleration (P_a); thus,

$$P = P_a + P_L \qquad [W]$$

Since power is equal to the product of force and velocity, the above expression becomes:

$$P(v) = P_a(v) + F_D\,(v)\,.\,v \qquad W$$

or

$$P(v) = P_a(v) + C_1\,v + C_2v^2 + C_3v^3 \qquad W \tag{B-23}$$

The development of $F_D\,(v)\,.\,v$, the power required to overcome drag forces, is described in Section B.2 of this appendix.

The following paragraphs deal with the development of energy expressions for use in Cases I - III.

Case I

The vehicle acceleration, force, and power for Case I are given by the equations below:

$$a(v) = a_m\,; \tag{B-24}$$

$$F_a = Ma_m \qquad \text{where } V_o \leq V_c \leq V_1$$

$$P_a = Ma_m\,v$$

The parameter M represents loaded vehicle mass and as such must be adjusted accordingly to account for vehicle capacity and actual occupancy. Combining Equations B-22 and B-23 yields an energy relationship among the parameters, and variables of interest are obtained.

$$E_1(v) = \frac{1}{a_m} \int_{V_o}^{v} \left[(Ma_m + C_1)\,v + C_2\,v^2 + C_3\,v^3\right] dv \quad J$$

or upon evaluation

$$E_1\ (V_o,\ v) = \frac{1}{a_m}\left[\left(\frac{Ma_m + C_1}{2}\right)(v^2 - V_o^{\ 2}) + \frac{C_2}{3}\ (v^3 - V_o^{\ 3}) + \frac{C_3}{4}\ (v^4 - V_o^{\ 4})\right]\ J \qquad (B\text{-}25)$$

Case II

A second component of energy must be considered if the cruise velocity is in the range $V_c > V_1$. In this case, the vehicle acceleration is represented by the Equation B-26.

$$a(v) = \frac{a_m\ V_c - a_f\ V_1}{V_c - V_1} - \left(\frac{a_m - a_f}{V_c - V_1}\right) v \qquad m/s^2 \qquad (B\text{-}26)$$

or $a(v) = b - a\ v \qquad m/s^2$

where $b = \dfrac{a_m\ V_c - a_f V_1}{V_c - V_1}$

and $a = \dfrac{a_m - a_f}{V_c - V_1}$

The corresponding force and power associated with this portion of the acceleration maneuver is shown below:

$$F_a = M\ (b - a\ v) \qquad N$$

$$P_a = M\ (b - a\ v)v \qquad W \qquad (B\text{-}27)$$

Combining Equations B-22, B-23, and B-27 yields the following energy relationship.

$$E_2(v) = \int_{V_1}^{V_c} \frac{M\ (b\text{-}av)\ v + C_1 v + C_2 v^2 + C_3 v^3}{b\text{-}av}\ dv \qquad J$$

or upon evaluation

$$E_2(V_1,V_c) = \frac{C_1}{a}(V_c - V_1) + \frac{M}{2}(V_c^{\,2} - V_1^{\,2}) - \frac{C_3}{3a}(V_c^{\,3} - V_1^{\,3})$$

$$- \left[\frac{C_1 b}{a^2} + \frac{C_2\, b^2}{a^3} + \frac{C_3 b^3}{a^4}\right] \ln\left(\frac{b - aV_c}{b - aV_1}\right)$$

$$- \frac{1}{2}\left[\frac{C_2}{a^3} + \frac{C_3 b}{a^4}\right]\left[(b - aV_c)^2 - (b - aV_1)^2\right]$$

$$- 2b\left[\frac{C_2}{a^2} + \frac{C_3 b}{a^3}\right](V_c - V_1) \qquad [J] \qquad \text{(B-28)}$$

The total propulsive energy used under CASE II conditions is given by combining Equations B-25 and B-28 with B-20. Equation B-20 is repeated here for convenience.

$$E_a = E_1(V_o, v)\Big|_{v = V_1} + E_2(V_1, V_c) \qquad [J]$$

CASE III

The partial solution obtained for the CASE II conditions (Equation B-28) is a valid one for the case where $V_o \geq V_1$. Here, the total propulsive energy required to accelerate a vehicle is given by Equations B-21 and B-28.

$$E_a = E_2(V_1, V_c)\Big|_{V_1 = V_o} \qquad [J]$$

It should be noted that, in general, the solution obtained for CASE II will be used for the AGT-SOS analyses. Further, the initial state of the vehicle will be defined as $V_o = 0$. The derived equations provide a measure of propulsive energy expended. To obtain the total energy needed for vehicle acceleration, one must combine these results with an efficiency factor which accounts for propulsion, controller, and drive train losses. The total energy (E_T) needed is derived from Equation B-29.

$$E = \eta\ E_T \qquad [J] \qquad \text{(B-29)}$$

where η = efficiency factor

Thus, the total energy required for acceleration is given by

$$E_T = \frac{E}{\eta} \qquad [J]$$

The above energy expressions have the units of joules (Watt-sec.). Generally, it is more convenient to work with kilowatt-hours (kW-h). This conversion is easily obtained by multiplying an energy measure in joules by the following factor.

$$\text{kW-h conversion factor} = \frac{1}{3.6\ (10)^6} \qquad \frac{\text{kW-h}}{\text{W - s}}$$

For example

$$E_T = \frac{E}{3.6\ \eta (10)^6} \qquad \text{kW-h}$$

B.5.2 ENERGY CONSUMPTION PER KILOMETER OF CRUISE

For the cruise portion of guideway travel, the force (F_m) or power (P_m) required to accelerate is zero and the resulting propulsive energy utilization is due to overcoming the external power losses (P_L) under steady-state conditions. The cruise energy is represented by the following expressions.

$$E_c = \int_{t_o}^{t_f} P_L\ (v)dt \qquad [J]$$

$$E_c = \int_{t_o}^{t_f} (C_1V_c + C_2V_c^{\ 2} + C_3V_c^{\ 3})\ dt \qquad [J]$$

$$E_c = (C_1 + C_2V_c + C_3V_c^2)\, V_c\, (t_f - t_o) \qquad J$$

$$\text{or} \quad E_c = (C_1 + C_2V_c + C_3V_c^2)\, X \qquad J \qquad \text{(B-30)}$$

where X = guideway distance traversed at constant velocity

In some instances, it may be more convenient to work with propulsive energy expended per kilometer (E_{ckm}). In this case, Equation B-30 is modified accordingly.

$$E_{ckm} = E_c/X \qquad J$$

$$E_{ckm} = C_1 + C_2V_c + C_3V_c^2 \qquad J \qquad \text{(B-31)}$$

The propulsive energy required for the cruise portion of a guideway trip is obtained from either Equation B-30 directly or Equation B-31 on a per-unit-of-travel basis.

The total energy expended is determined as before from Equation B-29 and the conversion to kW-h is accomplished by using the factor previously listed.

APPENDIX C

VEHICLE CONTROL ANALYSIS

Vehicle control can be addressed at various different levels in conjunction with the use of the SOS software. Detailed evaluations of the performance of vehicles under the control of particular algorithms and direct comparisons among alternative algorithms can be made through the use of the Detailed Operational Control Model (DOCM). Experiments which focus only on the performance of single vehicles or of many vehicles operating on a single guideway element are supported by the DOCM. At a higher level network effects of alternative control strategies can be evaluated using the Discrete Event Simulation Model (DESM). As a minimum, vehicle control must be addressed at an analytical level to provide input data for system-level performance and cost analyses. The more detailed analysis which supports control system design is described in an SOS report on operational control analysis.[19] The purpose of this section is to present the alternative algorithms to be considered in a system analysis, to indicate which algorithms are modeled by the DOCM and DESM, and to present procedures for calculating minimum headway and control system cost parameters.

C.1 ALTERNATIVE CONTROL ALGORITHMS

A specific combination of vehicle control, longitudinal control, and headway protection methods operating in conjunction with network merge and dispatch policies constitutes an operational control strategy. The individual strategy options which are implemented in at least one specific form for simulation using either the DOCM or DESM are defined in this section.

C.1.1 VEHICLE CONTROL

Vehicle control provides for regulation of vehicle position, velocity, acceleration, and jerk through acceleration and deceleration commands to the vehicle's propulsion and braking systems. The three regulation alternatives considered in the DOCM are:

1. Vehicle follower vehicle control implemented by fixed guideway blocks - For the purpose of vehicle control, the guideway is divided into discrete blocks, hard-wired to the guideway. Vehicle location, accurate only to the length of a fixed block, is determined from block occupancy data. A vehicle utilizes data on the occupancy status of preceding blocks and possibly data on its own velocity and position within a block to determine appropriate propulsion and braking commands. Central or local control may alter the algorithm which determines the propulsion and braking commands provided that the limits imposed by the headway protection strategy and maximum line speed are not violated.

2. Vehicle follower vehicle control implemented by continuous state measurements - Measurement equipment on board the vehicle provides essentially continuous measurement of inter-vehicle distance and relative velocity. These data along with nominal line speed data are used to determine propulsion and braking commands for the vehicle. When the inter-vehicle distance exceeds a function of safe stopping distance, the control is based entirely upon the nominal line velocity, and the vehicle controller is said to be in the velocity command mode. The vehicle is in the vehicle follower mode whenever the inter-vehicle spacing is less than or equal to the desired safe spacing.

3. Point follower vehicle control - Each vehicle follows a pre-determined velocity and position profile. These profiles may be interpreted as defining a virtual moving control point. On board measurement equipment provides essentially continuous measurements of the vehicle's position and velocity errors in tracking this control point, which are then used to determine propulsion and braking commands to keep the vehicle within a virtual slot having the control point as its center.

C.1.2 HEADWAY PROTECTION

Headway protection provides a fail-safe means of preventing inter-vehicle collisions. The two alternatives which are modeled in the DOCM are:

1. Fixed block headway protection - For the purpose of headway protection, the guideway is divided into discrete segments or blocks, hard-wired to the guideway. A vehicle is protected from colliding with a preceding vehicle through the imposition of velocity limit and braking commands based upon occupancy data received from preceding blocks. These commands specify a velocity envelope which may not be exceeded by the vehicle controller. The velocity limit and service or emergency braking commands to be used for a given block separation number are user input quantities. If the velocity limits are exceeded, the headway protection commands an emergency deceleration; or, if the block separation distance corresponds to a service or emergency brake situation, that command is issued.

2. Moving block headway protection - Measurement equipment on board the vehicle provides essentially continuous measurement of inter-vehicle distance and the vehicle's velocity. The velocity determines a minimum safe spacing. If the inter-vehicle distance becomes less than the safe stopping distance, an emergency braking command is given by this algorithm.

C.1.3 LONGITUDINAL CONTROL

Longitudinal control provides for the orderly movement of vehicles along the guideway and especially allows for the orderly merging of vehicles at merges and intersections. The three alternatives considered are:

1. Synchronous longitudinal control - Vehicles operate under point follower vehicle control, always tracking an initially assigned reference point.

2. Quasi-synchronous longitudinal control - Vehicles normally operate under point follower vehicle control but are allowed to advance or

slip from the initial reference point to another control point. This maneuver is performed upstream of a merge in a maneuver region and is made to resolve a merge conflict.

3. Asynchronous longitudinal control - Vehicles operate under vehicle follower vehicle control and are allowed to change velocity and position relative to the surrounding vehicular states to resolve a potential merge conflict.

These three commonly identified longitudinal control strategies are actually a higher level description of combinations of vehicle control and merge strategy.

C.1.4 MERGE STRATEGY

Merge strategy refers to the logic used to resolve potential merge conflicts. The three basic alternatives considered in both the DOCM and the DESM are:

1. Scheduled merge - The dispatch time for each vehicle is chosen so that as long as a vehicle adheres to its schedule, no merge conflicts will occur. If a vehicle cannot maintain its schedule, a conflict may occur and must be resolved by one of the other merge strategies. In the DESM, deterministic dispatching, which is described in the next section, is invoked to effect a scheduled merge maneuver. There is no algorithm associated with scheduled merge in the DOCM.

2. First-in/first-out merge (FIFO) - Vehicles are allowed to proceed through a merge based upon the time order in which they enter a data acquisition area (or zone of influence) located upstream of the merge point. This merge strategy is modeled in both the DOCM and the DESM.

3. Priority merge - Vehicles in a data acquisition area located upstream of the merge point are allowed to proceed through the merge in an order based upon a method of assigning priority other than

time order of arrival. Some examples of priority assignment are one favored link, loaded vehicles favored, moving vehicles favored, queued vehicles favored, random choice, alternating choice, etc. The priority merge algorithm which has been implemented in the DOCM for vehicles operating under vehicle follower vehicle control gives priority to vehicles in the analysis region of one link over the vehicles in the analysis region of the other link. Under point follower vehicle control, the DOCM user can specify the priority of one link over another in the event that vehicles arrive at merge decision points simultaneously. The DESM also accepts user input to identify priority links at merge junctions. In addition, the DESM permits vehicles entering the main line from an off-line station to be assigned priority over main line vehicles on the basis of their empty or loaded status.

C.1.5 DISPATCH STRATEGY

Dispatch strategy governs the degree of merge conflict resolution that is accomplished before a vehicle is launched onto the main line. A dispatch strategy is not implemented in the DOCM. Injections of individual vehicles into the DOCM simulation are either user specified or are randomly generated to satisfy input distribution statistics. As a simulator of isolated network elements, no dispatch strategy is required. However, the following three alternatives are implemented in the DESM:

1. Deterministic dispatch - All merge conflicts are resolved before launch, and barring failures, each vehicle is assured of traversing the network on a pre-assigned path in a predetermined time.

2. Quasi-deterministic dispatch - Merge conflicts are not resolved prior to launch, but information about the future state of the network is used to launch vehicles at times which provide a high probability of efficient merging.

3. Non-deterministic dispatch - Potential conflicts at merges are not considered before launch but are resolved locally in data acquisition and maneuver areas upstream of each merge.

C.1.6 COMPATIBLE COMBINATIONS

A specific combination of the control strategies just defined constitutes the system operational control policy. The individual strategies, however, are not completely independent; that is, certain combinations are not feasible. Synchronous and quasi-synchronous longitudinal control may use only point follower vehicle control, and asynchronous longitudinal control may use either of the two forms of vehicle follower vehicle control. Synchronous longitudinal control is only compatible with a deterministic dispatch strategy, and a deterministic dispatch strategy is only compatible with point follower vehicle control. Since a deterministic dispatch strategy implies that all merge conflicts have been resolved at the time a vehicle enters the guideway, the only compatible merge strategy is scheduled merge. The vehicle control and headway protection combination consisting of a vehicle follower vehicle control implemented using fixed block occupancy data and moving block headway protection is feasible, but it does not appear to use data in an efficient manner.

Six primary types of operational control are identified based upon the choice of longitudinal control and dispatch strategy as shown in Table C-1.

TABLE C-1. PRIMARY TYPES OF OPERATIONAL CONTROL

Longitudinal Control	Dispatch Strategy		
	Deterministic	Quasi-Deterministic	Non-Deterministic
Synchronous	Type 1	—	—
Quasi-Synchronous	Type 2	Type 3	Type 4
Asynchronous	—	Type 5	Type 6

Within each of these operational control types, there are alternate configurations which are feasible for practical implementation. Types 1, 2, 3, and 4 have point follower vehicle control and may have either fixed or moving block headway protection. Types 5 and 6 may each have the following four combinations of vehicle control and headway protection:

1. Fixed block headway protection and vehicle follower vehicle control implemented by fixed block measurements

2. Fixed block headway protection and vehicle follower vehicle control implemented by continuous measurements

3. Moving block headway protection and vehicle follower vehicle control implemented by continuous measurements

4. Moving block headway protection and vehicle follower vehicle control implemented by fixed block measurements

In addition to these subtype differences, Types 3, 4, 5, and 6 operational control may have either a first-in/first-out, or priority merge strategy. Types 1 and 2 operate under a scheduled merge policy. Potential operational control policies resulting from a combination of individual compatible strategies are summarized in Table C-2. The DOCM explicitly models all elements of operational control listed in the table except the dispatch function. Thus, the operational control strategies listed under Types 1, 2, and 5 represent the different strategies which can be modeled by the DOCM. The DOCM does accept a user defined vehicle injection file, so the analyst can represent differences due to alternative dispatch algorithms by specifying different injection files. The DESM, on the other hand, does model alternative dispatch policies, but it does not differentiate between alternative headway protection schemes. Thus, the combinations listed in Table C-2 which are modeled by the DESM include one combination from types 1, 2, 3, and 4 and two combinations from types 5 and 6 (i.e., 5a, 5b, 6a, 6b). The operational control model in the DESM does not distinguish, for example, between types 1a and 1b which differ only in the headway protection strategy. While block vehicle follower (VFB) vehicle control is modeled in

TABLE C-2. COMPATIBLE OPERATIONAL CONTROL STRATEGY COMBINATIONS

Type	Longitudinal Control	Dispatch	Vehicle Control	Headway Protection	Merge
1a	SY	D	PF	FB	S
1b	SY	D	PF	MB	S
2a	QS	D	PF	FB	S
2b	QS	D	PF	MB	S
3a	QS	QD	PF	FB	F, P*
3b	QS	QD	PF	MB	F, P
4a	QS	N	PF	FB	F, P
4b	QS	N	PF	MB	F, P
5a	A	QD	VFB	FB	F, P
5b	A	QD	VFC	FB	F, P
5c	A	QD	VFC	MB	F, P
5d	A	QD	VFB	MB	F, P
6a	A	N	VFB	FB	F, P
6b	A	N	VFC	FB	F, P
6c	A	N	VFC	MB	F, P
6d	A	N	VFB	MB	F, P

*First-In/First-Out and Priority merge strategies are both compatible, resulting in two combinations

Legend

A - Asynchronous
D - Deterministic
F - First-In/First-Out
FB - Fixed block
MB - Moving block
N - Non-Deterministic
P - Priority
PF - Point follower
QD - Quasi-Deterministic
QS - Quasi-Synchronous
S - Scheduled
SY - Synchronous
VFB - Fixed block vehicle followe
VFC - Continuous vehicle follower

the DESM, it should be used in modeling AGT systems only in carefully selected cases. When it is specified, the user is constrained to a single value of minimum headway for all network links, and the link lengths are modified by the Input Processor so that the length of each link is an integral number of blocks. For long headway systems deployed on networks having short links, this procedure can significantly alter the total length of guideway and station spacing in the network being modeled. As indicated in Section 3.0 on network modeling, it is sometimes useful to specify different values of minimum headway on different links.

C.2 MINIMUM HEADWAY EQUATIONS

The minimum operational headway associated with a specific combination of operational control strategies depends on the strategies chosen and on the type of stations (on-line or off-line) in the network. In this section general expressions for the calculation of minimum headway are presented for the case of both off-line stations and on-line stations. An analysis of how these equations are applied to the evaluation of minimum headway for specific combinations of operational control strategies is presented in Reference 19.

C.2.1 MINIMUM HEADWAY FOR SYSTEMS WITH OFF-LINE STATIONS

In this section two expressions are presented for the minimum head-to-head distance between vehicles considering only the dynamics of braking to a safe stop. The first expression is rather general, and the other one is a very useful special case of the general expression.

The following equation gives a worst-case head-to-head distance that must be allowed in order for a trailing vehicle to brake to a stop without colliding with a failed lead vehicle.

$$
\begin{aligned}
D_m = {} & \frac{v^2}{2A_e} + \frac{vA_e}{2J_e} + \tau v + \frac{vA_f}{J_e} + \frac{vA_f^2}{2A_eJ_e} + \frac{\tau vA_f}{A_e} \\
& + \frac{\tau A_f^3}{2A_eJ_e} + \frac{A_f^4}{8A_eJ_e^2} + \frac{\tau^2A_f^2}{2A_e} + \frac{A_eA_f^2}{4J_e^2} \\
& + \frac{\tau A_eA_f}{2J_e} + \frac{A_f\tau^2}{2} + \frac{A_f^3}{3J_e^2} + \frac{A_f^2\tau}{J_e} + L
\end{aligned}
\tag{C-1}
$$

where

D_m = Head-to-head vehicle distance

v = Trailing vehicle velocity at the time of failure detection

A_e = Trailing vehicle emergency deceleration (DOCM variable ANEACC)

J_e = Trailing vehicle emergency jerk (DOCM variable ANEJRK)

τ = Reaction delay after failure detection (DOCM variable ANEDLY)

A_f = Trailing vehicle acceleration at failure

L = Preceding vehicle (or consist) length (DOCM variable IDVLEN)

The acceleration time history for such a braking situation is shown in Figure C-1. This expression also assumes "brickwall" stops for the failed lead vehicle; that is, its deceleration rate is infinite. This expression is very conservative. A commonly-used subcase assumes that the trailing vehicle acceleration at failure is zero. This is not unrealistic since

first, a vehicle's acceleration limit at maximum design velocity is usually less than its low velocity acceleration capability and secondly, because a nonzero value at maximum design velocity implies a double failure event. The double failure event is that the lead vehicle has failed and the trailing vehicle is in an acceleration mode at minimum acceptable spacing, itself a failure event. The expression when A_f is zero becomes:

$$D_m = \frac{v^2}{2A_e} + \frac{vA_e}{2J_e} + \tau v + L \qquad \text{(C-2)}$$

The safe headway distance D in all DOCM algorithms is

$$D = BD_m \qquad \text{(C-3)}$$

where Equation C-2 is the expression used for D_m, and B is the user input variable ANBFCT.

When head-to-head vehicle distance becomes less than this value, an emergency procedure is enabled. Thus, the commanded spacing for vehicle control algorithms must be greater than this distance. In general, the magnitude of this extra distance and the reaction time (τ) in Equation C-2 are different for each combination of operational control strategy. The most significant difference is due to the focusing effect associated with on line speed reductions in point follower systems.

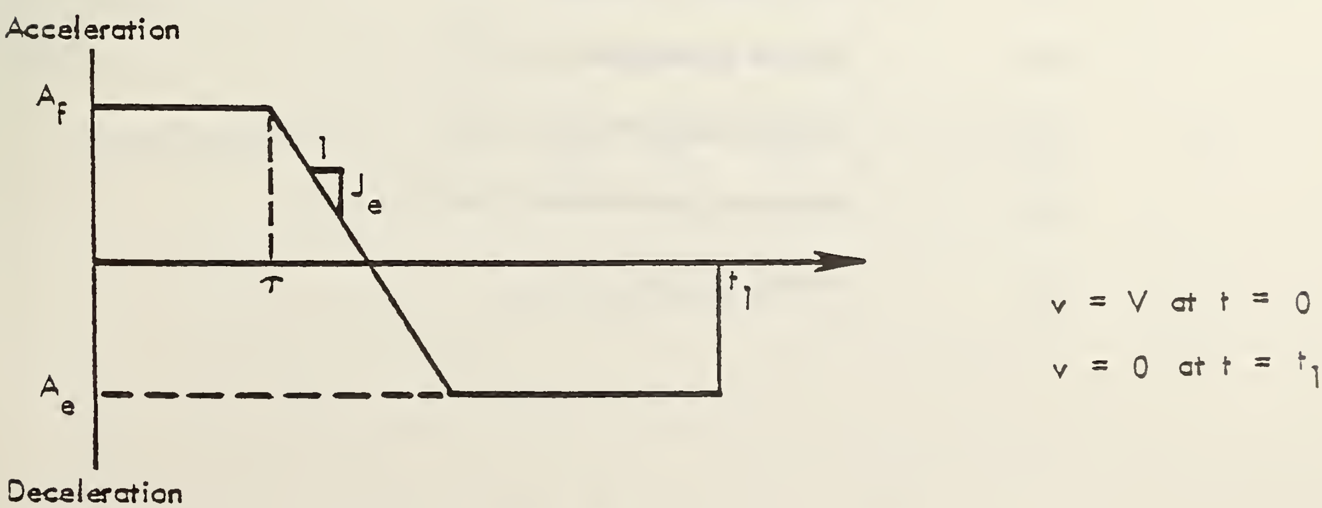


FIGURE C-1. ACCELERATION TIME HISTORY ASSOCIATED WITH EQUATION C-1

C.2.2 MINIMUM HEADWAY FOR SYSTEMS WITH ON-LINE STATIONS

The equations that were developed to estimate minimum safe headway for systems with on line stations are based on work by Bergmann.[37] The first set of equations apply for cases in which vehicles accelerate from stations at a constant rate, a_m. The first headway equation presented below applies when trains are relatively short while the second one is used when trains are relatively long.

$$H_t\,(\text{min}) = t_d + t_r + \sqrt{2L\left(\frac{1}{a_m} + \frac{1}{d_s\,(1-d_s/d_e)}\right)} \qquad \text{(C-4)}$$

when

$$L \leq \frac{V_c^2}{2}\left(\frac{1}{a_m} + \frac{1}{d_s} - \frac{1}{d_e}\right) \qquad \text{(C-5)}$$

$$H_t\,(\text{min}) = t_d + t_r + \frac{L}{V_c} + \frac{V_c}{2}\left(\frac{1}{a_m} + \frac{1}{d_s} + \frac{1}{d_e}\right) \qquad \text{(C-6)}$$

when

$$L > \frac{V_c^2}{2}\left(\frac{1}{a_m} + \frac{1}{d_s} - \frac{1}{d_e}\right) \qquad \text{(C-7)}$$

where

H_t (min) = Minimum headway in seconds

t_d = Dwell time at stations in seconds

t_r = Reaction time, i.e. time required to detect a failure and to initiate a response in seconds

L = Train length in metres

a_m = Service acceleration in m/s^2

d_s = Service deceleration in m/s^2

d_e = Emergency deceleration in m/s^2

V_c = Cruise velocity in m/s

The acceleration profiles developed in Appendix B have the characteristic that the acceleration is constant up to a velocity, V_1, and then it decreases linearly with velocity due to power limitations of the propulsion system. Equations C-4 and C-6 can be used only when the minimum headway condition occurs at a lead vehicle velocity below V_1, where the acceleration is constant. The velocity of the leading train at which the minimum headway condition occurs is given by

$$V\,(H_t\ \text{min}) = \sqrt{\frac{2L}{\frac{1}{a_m} + \frac{1}{d_s\,(1 - d_s/d_e)}}} \qquad \text{(C-8)}$$

If the velocity corresponding to the minimum headway condition, $V\,(H_t$ min), is greater than V_1, the velocity limit for constant acceleration, then Equations C-4 and C-6 do not apply. To permit the estimation of minimum headway for this case, an upper bound for minimum headway is established by assuming that the train leaving the station does not accelerate beyond V_1, i.e., it is assumed to move out of the station area more slowly than it actually does. The following equation is a conservative estimate (somewhat high) of minimum headway which is used when $V\,(H_t$ min) is greater than V_1:

$$H_t\ \text{min (upper bound)} = t_d + t_r + \frac{V_c}{d_s} + \frac{L}{V_1} + \frac{V_1}{2}\left[\frac{1}{a_m} + \frac{1}{d_s(1 - d_s/d_e)}\right] \qquad \text{(C-9)}$$

C.3 CONTROL BLOCK SPECIFICATION

The objective of this methodology is not to design control systems, but rather to provide a consistent means for estimating control system costs. For deployments in which a block control system is a viable control alternative, the methodology represents a reasonable estimate of block count for a control system of modest sophistication. For cases in which no actual blocks are present, the methodology is meant to arrive at a realistic estimate of the cost of continuous control.

The methodology used to estimate the number of control blocks on guideway links, at merges and diverges, and in stations is described below. The number of control blocks on each guideway link, including the bypass links of off-line stations, is estimated according to the following formula:

$$\text{Blocks} = \text{Integer}\left(\frac{3\,(D - D_a - D_d)}{Vh}\right) - 1 \qquad \text{(C-10)}$$

where: D = link length

D_a = vehicle acceleration distance associated with an on-line station at the upstream end of the link

D_d = vehicle deceleration distance associated with an on-line station at the downstream end of the link

V = link cruise velocity

h = link headway time

The "station bypass links" of on-line stations, which are defined in the network input to the DESM, are not considered since they are considered in the block count for stations. The value of link headway, h, in Equation (C-10), is often not the link headway time entered for the DESM simulation, and selection of its specific value is at the discretion of the analyst. Guidelines which can be used to select the value of h to use in Equation C-10 are as follows:

1. For synchronous or quasi-synchronous systems, the maximum slot headway time which provides acceptable system performance should be selected.

2. For systems with asynchronous control and scheduled service, the combined average headway of the routes using each link during the peak demand period should be used. To provide a margin of safety, or to accommodate a slight increase in vehicle flow, 75 percent of the average headway can be specified.

3. For asynchronous systems with demand responsive service and off-line stations, the actual headways on each link cannot easily be determined. The values can be determined by analyzing a great deal of simulation output. However, an average headway value applicable to the entire system is available from the Performance Summary Report produced by the DESM. This average headway value is given by the following formula:

$$h = \frac{(3600) * \text{number of guideway links}}{\text{maximum number of vehicles leaving links per hour}}$$

The .75 factor should again be applied. This headway value is appropriate because the minimum headway time specified for the system is, in many cases, much less than the value actually utilized by the system. Since the purpose of the procedure is not to design a control system in any detail, but to estimate costs on a rather high level, the use of average headway is justified.

Seven blocks are assumed for each guideway merge -- three blocks per link upstream of the merge and one block downstream of the merge point as shown in Figure C-2. One block per link downstream of a diverge point is assumed as shown in Figure C-3 for a total of two blocks per diverge.

On-line stations, which have a total capacity of less than, or equal to, three trains are assumed to have a total of four blocks per station. Three blocks (including one for the dock) are provided to control the deceleration maneuver and one block is provided to control the acceleration maneuver. Figure C-4 illustrates the blocks in a typical on-line station.

A typical off-line station combines these requirements with those of the merge and diverge. As illustrated in Figure C-5, a minimum of 13 blocks are required for each off-line station. As stations, either on-line or off-line, become more complex due to an increase in link capacity or number of links, additional control system cost is incurred. The cost of this additional complexity is estimated as the equivalent of one control block per unit of capacity in excess of three trains not including possible storage and storage connection link capacity. The control system cost associated with these types of station links is assumed to be one control block for each storage and storage connection link which is defined. In addition, if parallel docks are provided, control blocks for the additional merge and diverge are required.

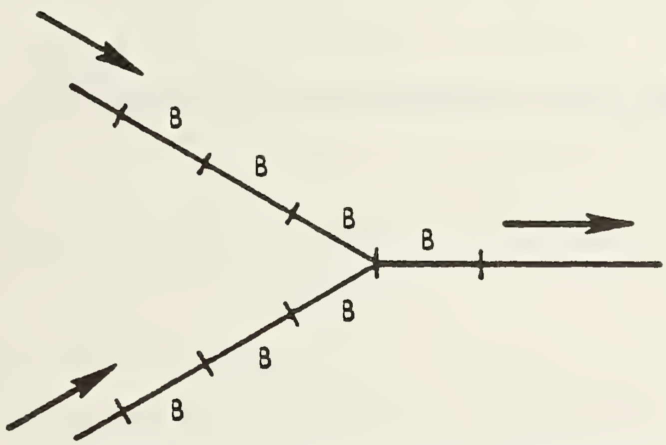


FIGURE C-2. ADDITIONAL MERGE BLOCKS

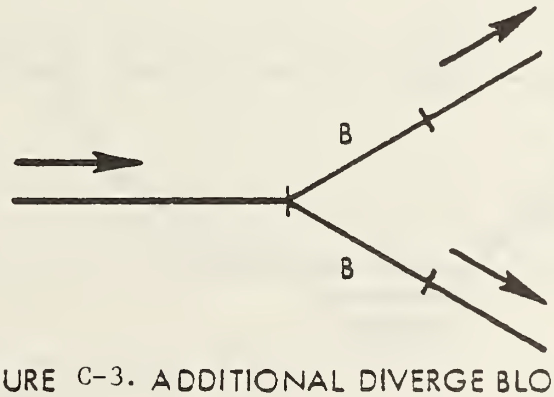


FIGURE C-3. ADDITIONAL DIVERGE BLOCKS

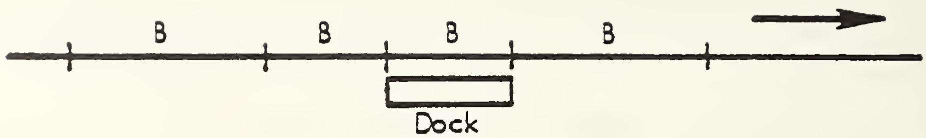


FIGURE C-4. TYPICAL ON-LINE STATION BLOCKS

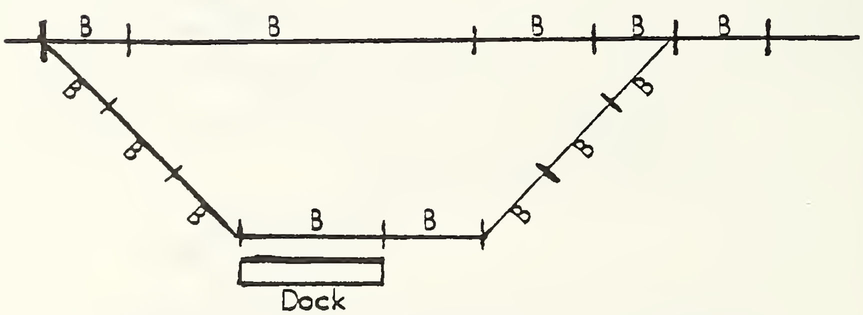


FIGURE C-5. TYPICAL OFF-LINE STATION BLOCKS

APPENDIX D

STATION ANALYSIS

Stations represent a significant portion of the capital cost of an AGT system. The purpose of applying the station analysis procedure described in this appendix is to specify station designs to support the estimation of system costs. For this purpose, the designs need only be specified functionally in terms of areas and numbers of devices. The basic analysis procedure consists of establishing and then minimizing the life cycle costs of stations subject to a set of constraints representative of the demand environment considered. Principally, the constraints reflect service level goals measured in terms of maximum delay time, minimum station area per passenger, and service device redundancy.

In the station sizing procedure, the size and equipment requirements of various functional areas within each station are determined. Before applying the procedure, it is necessary to generate a functional description of the stations under consideration. In general, stations consist of three functional areas: an entrance-exit region, a pedestrian vertical displacement region, and a vehicle boarding platform. Figure D-1 illustrates the general configuration of a bi-level, center-platform station.

A total of five activities are associated with the entrance-exit region of the station: three for pedestrians entering the station and two for persons leaving. For those coming into the station, these activities include:

- Entering the free portion of the station
- Acquiring a ticket or correct fare
- Processing through a fare collection turnstile

For persons leaving the station, activities within this region include:

- Processing through an exit turnstile
- Exiting the station

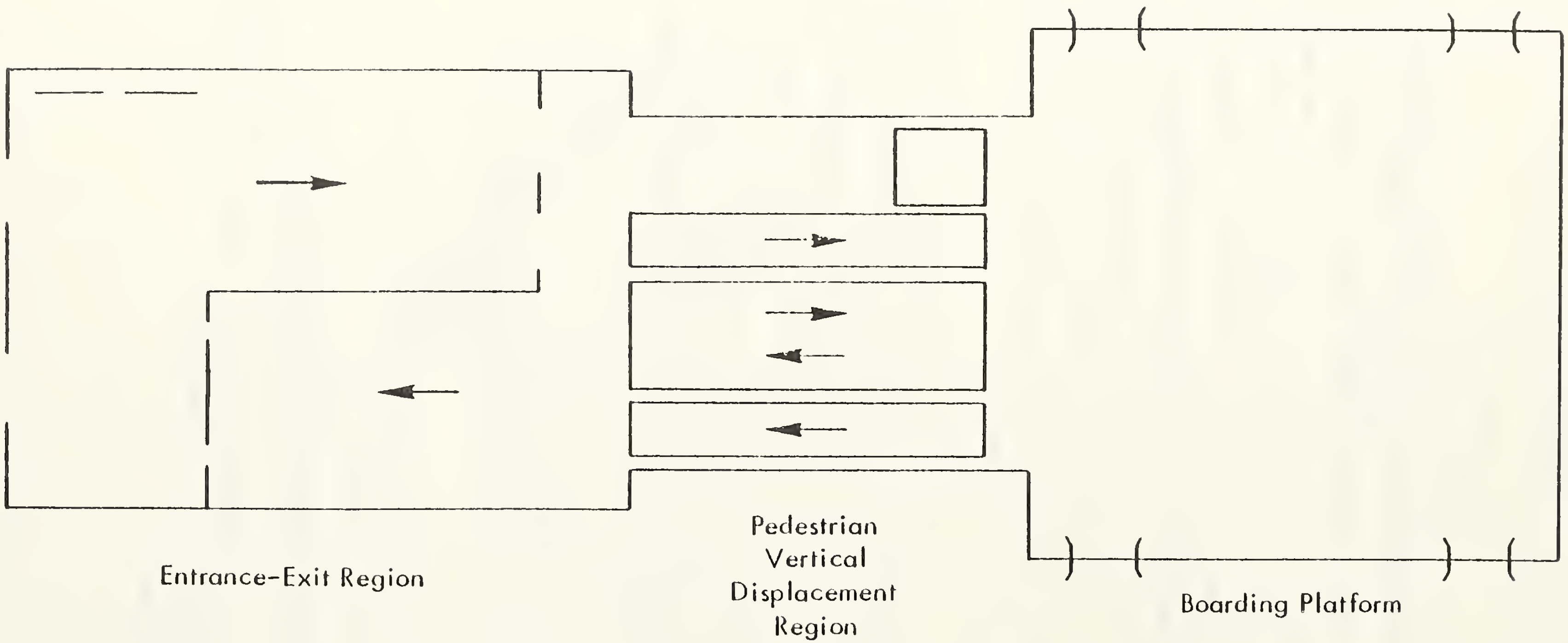


FIGURE D-1. GENERAL BI-LEVEL STATION CONFIGURATION

In addition to the space required for processing devices, queuing area is provided at the ticketing equipment and at the turnstiles, and walk space is provided between activities areas.

Within bi-level stations, it is assumed that the entrance-exit region is at a different elevation from the vehicle boarding activity. Pedestrians are conveyed between these two levels within the vertical displacement region by means of stairs, escalators, or elevators.

Stairs and escalators, when employed, are designed to a capacity such that no queues will form at their access points under the assumption of a uniformly distributed peak period pedestrian arrival rate. Minimal queuing area is provided at elevator entrances.

The vehicle boarding region functions primarily as a point of vehicle egress and ingress. Pedestrians also use the platform as a queuing area while awaiting vehicle arrivals.

At transfer stations where it is either impossible or undesirable to dock all vehicles at a single platform, multiple vehicle boarding regions are provided and interconnected by pedestrian walkways and additional vertical movement facilities.

The distinction is made with regard to platform types as to whether vehicles dock on only a single side or on both sides. This is primarily in order to determine the number of platform gates necessary and does not affect the platform region size. In some station configurations designed to serve dual lane guideway, two platforms are provided along with the required pedestrian walkways and vertical movement facilities.

Guidelines to be used to size these station areas according to expected demand are based on the principles of pedestrian planning and design developed by Fruin.[38] Fruin has correlated the required floor area for pedestrian activities and demand for those activities with a measure of level of service. Results of his work which are directly applicable to station design are reproduced in Table D-1. A conversion from the English units of the original work to metric units has been made. The station

TABLE D-1. LEVEL OF SERVICE CLASSIFICATIONS FOR PEDESTRIAN QUEUES, WALKWAYS AND STAIRWAYS

Level of Service	QUEUES	PEDESTRIAN WALKWAYS		STAIRWAYS	
	Average Pedestrian Area Occupancy (m^2/person)	Average Pedestrian Area Occupancy (m^2/person)	Average Pedestrian Flow Volume (Persons/meter width/minute)	Average Pedestrian Area Occupancy (m^2/person)	Average Pedestrian Flow Volume (Persons/meter width/minute)
A	1.208 or more	3.253 or more	22.96 or less	1.859 or more	16.40 or less
B	0.925 to 1.208	2.324 to 3.253	22.96 to 32.80	1.394 to 1.859	16.40 to 22.96
C	0.651 to 0.925	1.394 to 2.324	32.80 to 49.20	0.930 to 1.394	22.96 to 32.80
D	0.279 to 0.651	0.930 to 1.394	49.20 to 65.60	0.651 to 0.930	32.80 to 42.64
E	0.186 to 0.279	0.465 to 0.930	65.60 to 82.00	0.372 to 0.651	42.64 to 55.76
F	0.186 or less	0.465 or less	up to 82.00	0.372 or less	Variable to 55.76

design guidelines developed during the System Operations Studies and presented in this appendix assume level of service C.

A number of different types of service devices are necessary in order to process persons through the station regions. Briefly these include:

- Ticketing equipment
- Turnstiles
- Elevators
- Escalators
- Platform doors

A brief description of the characteristics and requirements of these devices is presented below.

Ticketing equipment can range in complexity from a simple change machine to a sophisticated computer interface which makes reservations on demand responsive vehicles and computes zone fares. For most systems, a single-use ticket vending device is adequate. Service rates, required floor area, and estimated cost data for ticketing equipment appear in Tables D-2, D-3, and D-4 respectively.

Turnstiles, or devices which function equivalently, are used to separate the free and paid sections of the station. Entrance turnstiles allow pedestrians to flow from the free to the paid station region. In the process a fare is collected by one of the following means.

(1) Accepting a coin or coins

(2) Accepting and then returning a multi-use fare card

(3) Accepting and capturing a single-use fare card

Exit turnstiles function to permit passage from the paid to the free region of the station.

Turnstile data found applicable to the station sizing process appear in Tables D-3, D-4, and D-5. In the SOS analysis, a pedestrian flow capacity of 20 persons per minute per device was used for entrance turnstiles and 24 persons per minute per device for exit turnstiles.

Elevators are provided at bi-level stations for the use and convenience of those persons who might find it difficult to use an alternate means of

TABLE D-2. TICKETING EQUIPMENT SERVICE RATES

	Service Rate (persons/minute)
Change Vending	5-8
Ticket Issuing	
Single Fare	5-8
Multi Fare	3-7

TABLE D-3. STATION EQUIPMENT DIMENSIONS AND MINIMUM DESIGN QUEUEING AREA

Equipment Type	Width (m)	Depth (m)	Total Floor Area (m^2)	Minimum Queue Area (m^2)
Ticketing Device	1.0	1.0	1.0	1.0
Turnstile	1.0	2.0	2.0	1.0
Elevator	2.44	2.13	5.20	2.44

TABLE D-4. STATION EQUIPMENT COST DATA

Equipment Type	Base Year Cost	Life Cycle Cost	Reference
	($, 1977)	($, 1977)	21
Ticketing Device	18,420	82,438	21
Turnstile	14,736	65,991	21
Elevator	65,651	268,537	21
Escalator	52,521	214,830	21
Platform Door	11,052	49,463	21

TABLE D-5. TURNSTILE SERVICE RATES*

Turnstile Operating Principle	Mean Inter-Arrival Time (sec.)	Pedestrian Volume (persons/minute)
Free Admission	1.0 - 1.5	40 - 60
Ticket Collector	1.7 - 2.4	25 - 35
Coin Operated Single Slot Double Slot	 1.2 - 2.4 2.5 - 4.0	 25 - 50 15 - 25

*Source: John J. Fruin, Pedestrian Planning and Design, page 53

conveyance. Data pertaining to the incorporation of elevators into the overall station design appear in Tables D-3 and D-4.

When included in a station design, escalators are considered as the primary source of conveyance between the two levels of a bi-level station. Cost, capacity, and floor area requirements appear in Tables D-4 and D-6.

Automatic doors or gates are included in the boarding platform design in order to provide access to the vehicles upon their arrival and to prohibit pedestrian intrusion onto the guideway structure between arrivals.

The number of these devices and the floor area required to serve the demand can be determined using the station sizing procedure illustrated in Figure D-2. The first steps in the station sizing procedure are to establish the pedestrian arrival rate to which the station is to be designed and to set a service level goal. The arrival rate used in the SOS station analysis is that of the peak demand period. The level of service goal used as a minimum design requirement is that the platform access time must be less than or equal to the average passenger wait time.

The next step is to establish a reasonable range of service device numbers to be considered in the analysis. Then, for all combinations of ticketing devices and turnstiles to be tested, Figure D-3 is applied to obtain the expected size of the turnstile queue. The data plotted in this figure were determined using the Detailed Station Model (DSM) assuming a turnstile service rate of 20 persons per minute. The expected maximum queue size is the sum of the mean and one standard deviation of the maximum queue size per 2-minute sampling interval generated by the DSM in a 60-minute simulation of station operation. The expected size of the ticketing device queue can be estimated from the turnstile queue size using the following relationship:

$$Q_1 = \frac{R2\ N2}{R_1\ N_1} Q_2\ P_1 \qquad \text{(D-1)}$$

TABLE D-6. ESCALATOR CAPACITY AND DESIGN DATA *

Capacity		Escalator Dimensions		Region Dimensions	
Maximum Theoretical (persons/hr.)	At 75% Utilization (persons/hr.)	Width at Hip (inches)	Width at Tread (inches)	Floor Width (m)	Minimum Queue Area (m^2)
5000 (a)	3750	32	24	1.42	1.42
6700 (b)	5025	32	24	1.42	1.42
8000 (a)	6000	48	40	2.36	2.36
10,700 (b)	8025	48	40	2.36	2.36
(a) Incline speed of 90 ft./min. (0.457 m/s), 68 steps/minute					
(b) Incline speed of 120 ft./min. (0.610 m/s), 89 steps/minute					

*Source: John J. Fruin, Pedestrian Planning and Design, Page 98

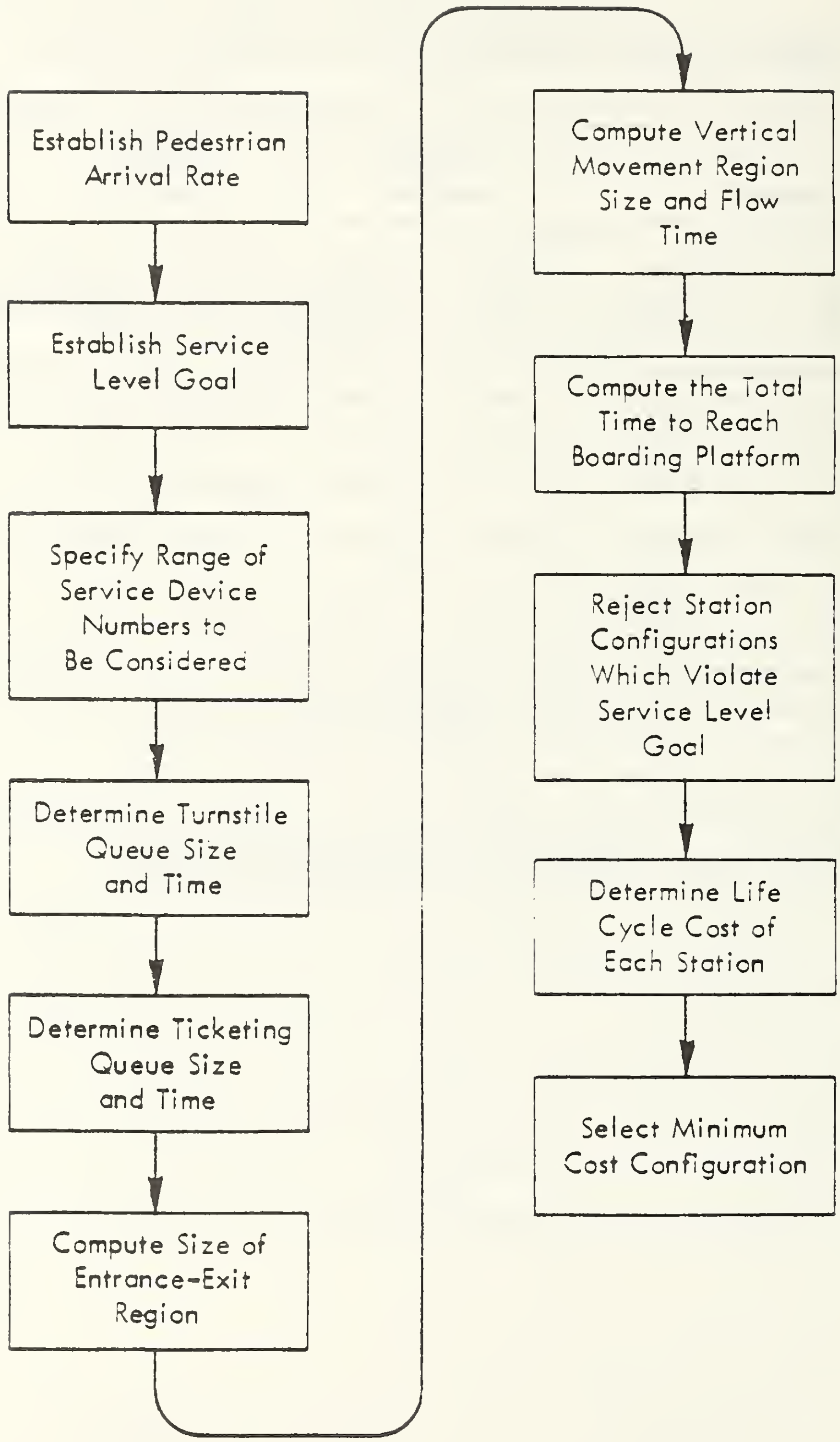


FIGURE D-2. STATION SIZING PROCESS

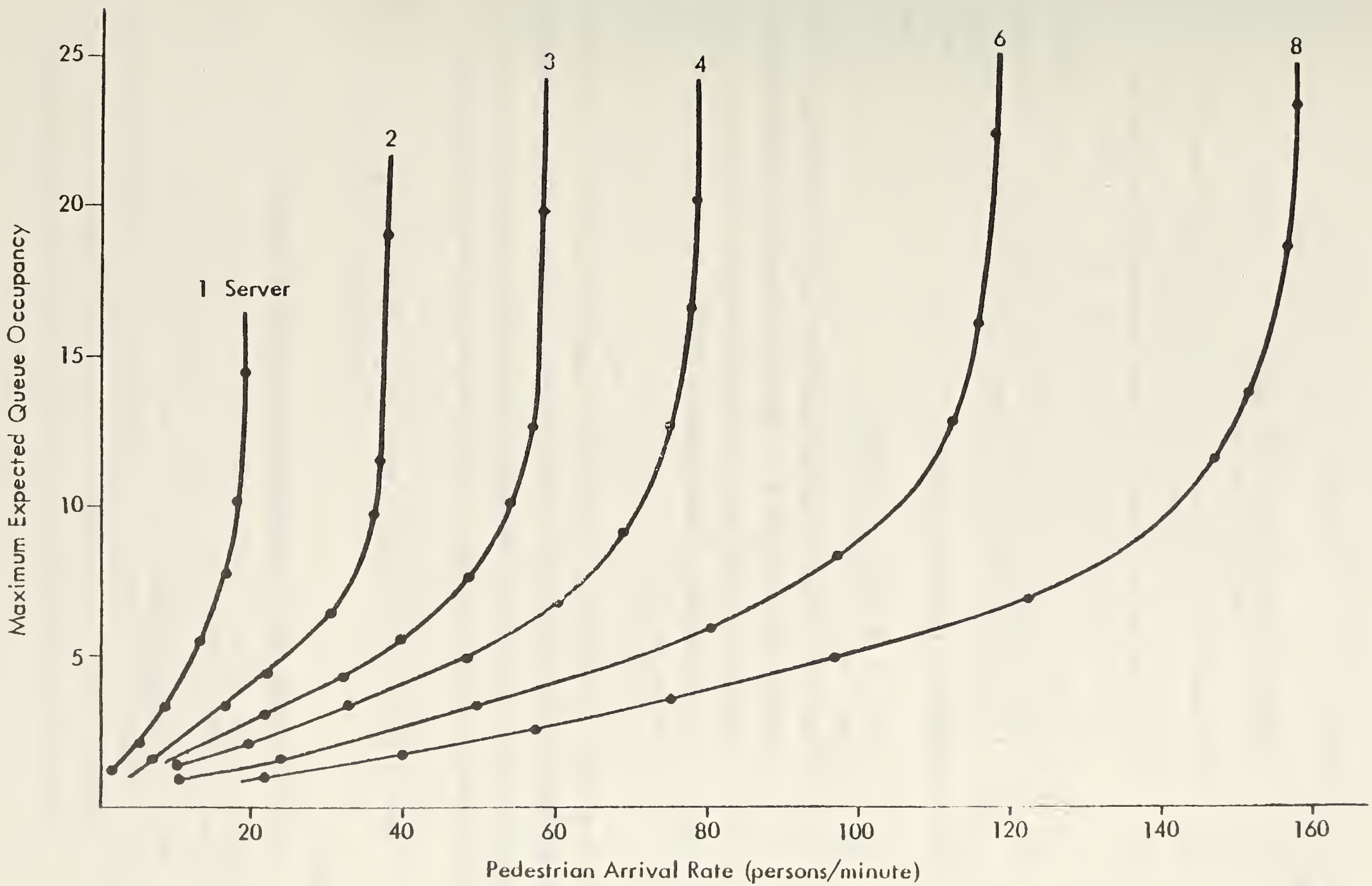


FIGURE D-3. EXPECTED MAXIMUM TURNSTILE QUEUE OCCUPANCY AS A FUNCTION OF PEDESTRIAN ARRIVAL RATE FOR A RANGE OF SERVICE DEVICE NUMBERS. TURNSTILE CAPACITY OF 20 PERSONS/MIN IS USED.

where

Q_1 = Ticketing device queue size, persons

Q_2 = Entrance turnstile queue size, persons (from Figure D-3)

R_1 = Ticketing device processing rate, persons/minute/device (6 persons/minute was assumed in the SOS analysis)

R_2 = Turnstile processing rate, persons/minute/device (20 persons/minute was assumed in the SOS analysis)

N_1 = Number of ticketing devices

N_2 = Number of entrance turnstiles

P_1 = Probability that arriving pedestrian uses a ticketing device (0.20 was used in the SOS analysis for scheduled systems; 1.0 was used for demand responsive systems since the patron must communicate his destination to the system.)

The time spent in ticketing or turnstile queues is estimated as the product of the service device processing time and the queue size divided by the number of service devices. The total time spent in the ticketing and turnstile regions, on the average, is given by the following relationship:

$$T_{TT} = \left[(T_W + T_p) *P + D/S\right]_{TK} + \left[(T_W + T_p)*P+D/S\right]_{TN} \qquad \text{(D-2)}$$

where

T_{TT} = Average time in ticketing and turnstile region

T_W = Time in queue

T_p = Processing time

P = Probability that a patron will find it necessary to use the service device

D = Walking distance across link (m)

S = Pedestrian walking speed (m/s)
(0.5 m/s assumed in the SOS analysis)

The subscripts TK and TN refer to the ticketing and turnstile events, respectively. The area of the ticketing and turnstile region is then computed for the set of station designs under consideration. Figure D-4 shows the area of this region for a range of turnstile queue occupancy and numbers of service devices.

From Figure D-4 it can be seen that the floor space required by any particular turnstile/ticketing device combination remains constant as the turnstile queue occupancy increases to a nominal value representing the minimum queue size for which the area is designed. This area increases linearly as the queueing area is lengthened to accommodate an increased number of persons queueing. In a conceptual station design that is basically rectangular, as higher turnstile queue occupancies are encountered, the linear increase in area required may give way to a parabolic increase. This can be due to a further requirement to widen the station to accommodate the increased queue in the ticketing region where more than the minimum floor area may be required. Thus it becomes possible to decrease the overall station floor area required in a station by increasing the number of ticketing devices beyond the minimum number of two for a given number of turnstiles.

The next step in the station sizing process is to determine the characteristics of the vertical movement region. For the station demands considered in the SOS analyses, the higher capacity of escalators relative to stairs was usually not sufficient to offset the higher capital cost. However, an elevator was specified for each station to accommodate the aged and infirm. The demand load which the elevator takes from the other vertical movement facilities (stairs or escalators) is assumed to be

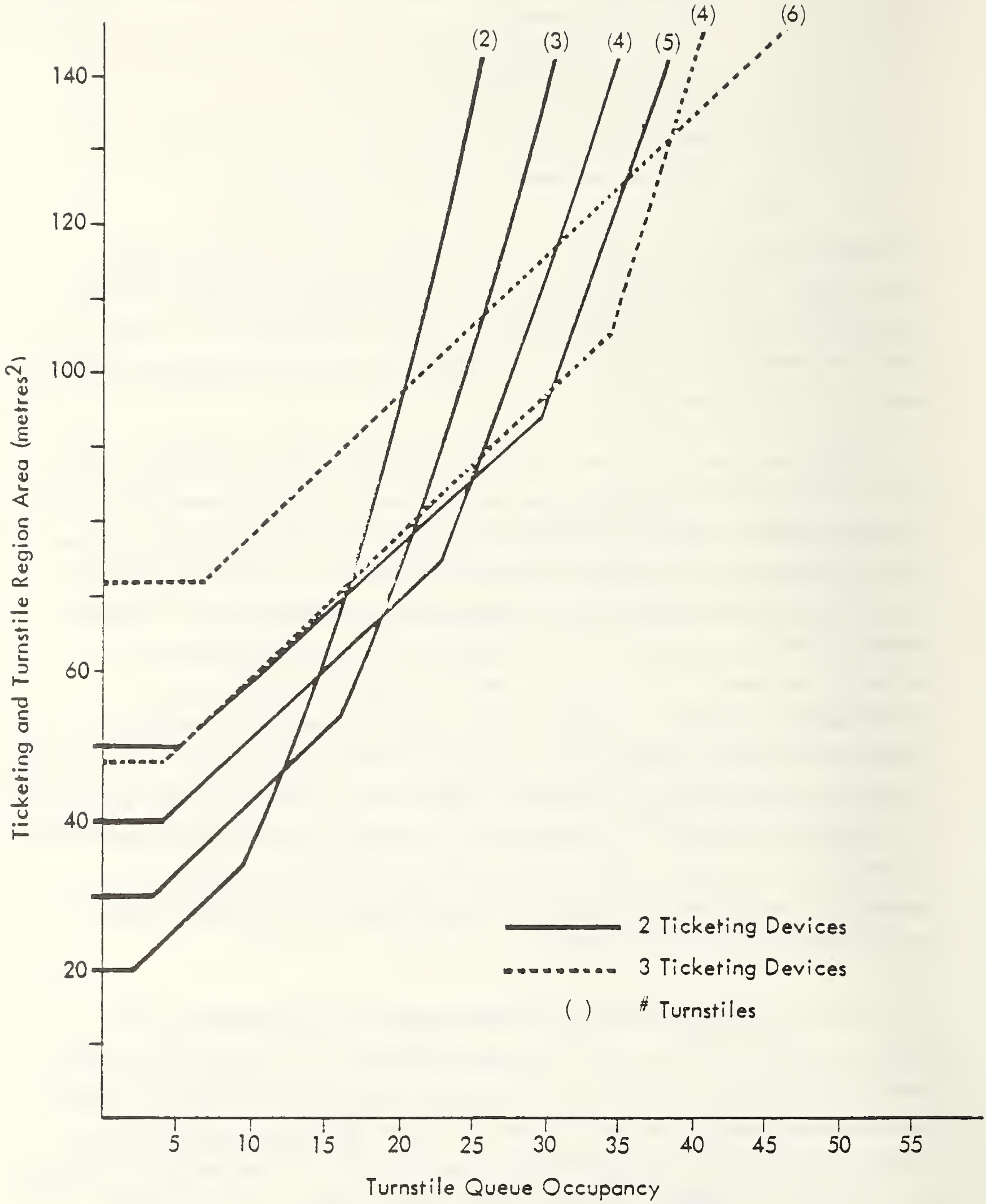


FIGURE D-4. TICKETING AND ENTRANCE-EXIT TURNSTILE REGION AREA AS A FUNCTION OF QUEUE SIZE

negligible and was ignored in sizing these other facilities. A minimum two-way stair width of 1.22 meters was used for all of the SOS deployments. A flow rate capacity of around 23 persons per minute for every meter width of stair is assumed. This results from a walking speed of 29 meters per minute with an occupancy factor of 1.115 square meters per person and a linear spacing of 1.26 meters per person. The station area required for stairs is shown in Figure D-5 as a function of demand and height differential. The time spent in the vertical movement region is computed by considering walk times and processing rates for stairs or escalators.

The expected platform access time is now determined for each of the station designs under consideration by summing the time spent in the entrance-exit region and the time spent within the vertical movement region. The resulting access time is then compared to the service goal previously established in order to eliminate all station configurations which fail to meet this goal.

The area of the boarding platform is then determined by considering the effects of train length, minimum width requirements for vertical movement facilities, and platform queue size as determined by the Discrete Event Simulation Model. This information can be determined using the DSM if vehicle arrival rate and occupancy information is known. However, vehicle occupancy and arrival rate are system characteristics which depend on passenger arrivals at other stations in the network. These characteristics are best determined by system simulation. The DESM produces a Vehicle Log for a selected station which contains the vehicle arrival information required as input to the DSM to support detailed analysis of a particular station. However, platform queue information is required for all stations in the network. The DESM generates the average and maximum platform queue size for each sampling interval of each station in the network. Since this information is already available as a result of system-level analyses, it can be used in the station analysis to size boarding platforms. The expected maximum platform queue occupancy used to evaluate platform size in the SOS analyses was taken as the sum of the sample mean of maximum queue occupancy and one standard deviation. Figure D-6 shows platform area as a function of platform queue size.

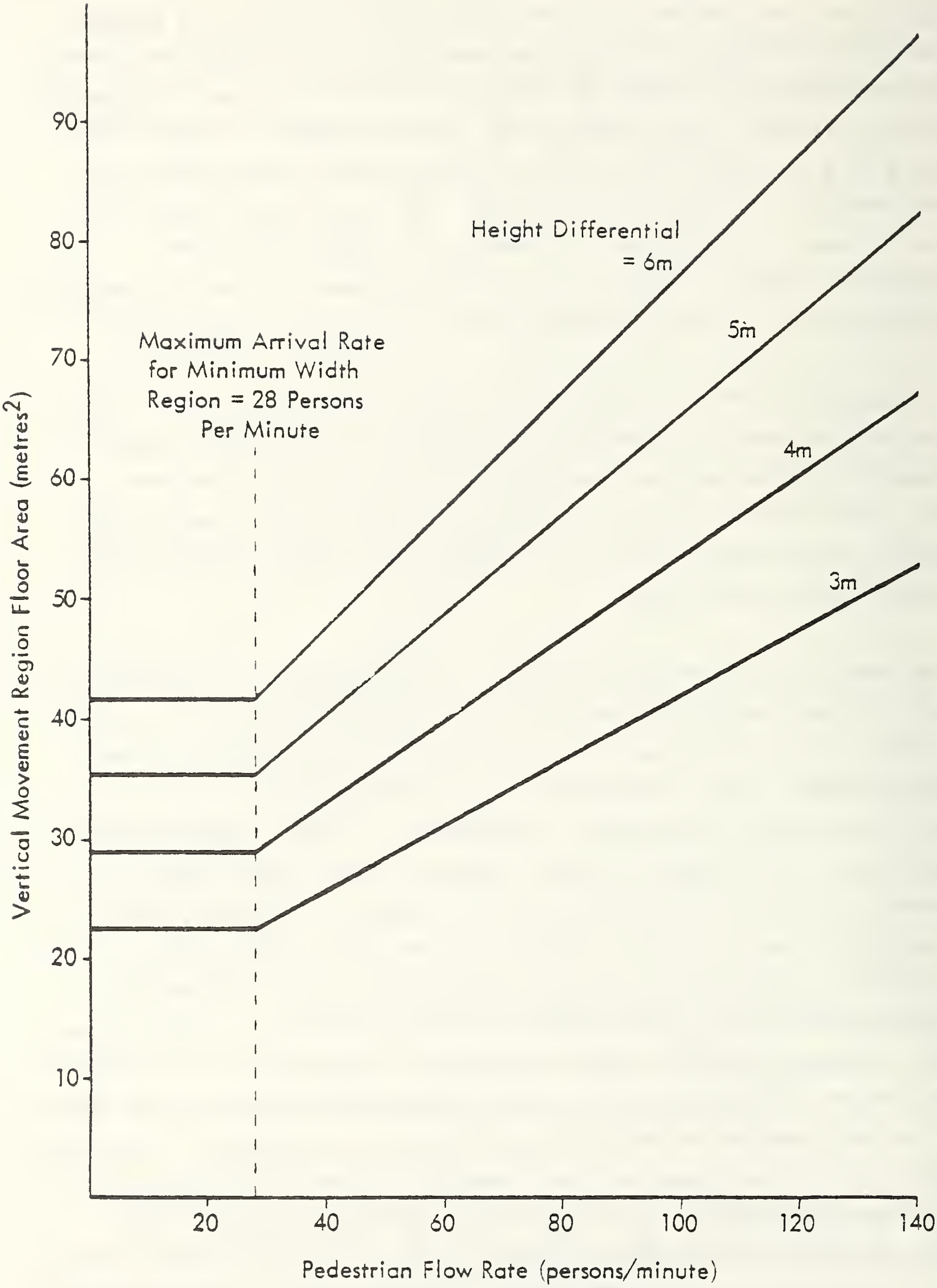


FIGURE D-5. STATION AREA REQUIRED FOR STAIRS AS A FUNCTION OF DEMAND AND HEIGHT DIFFERENTIAL

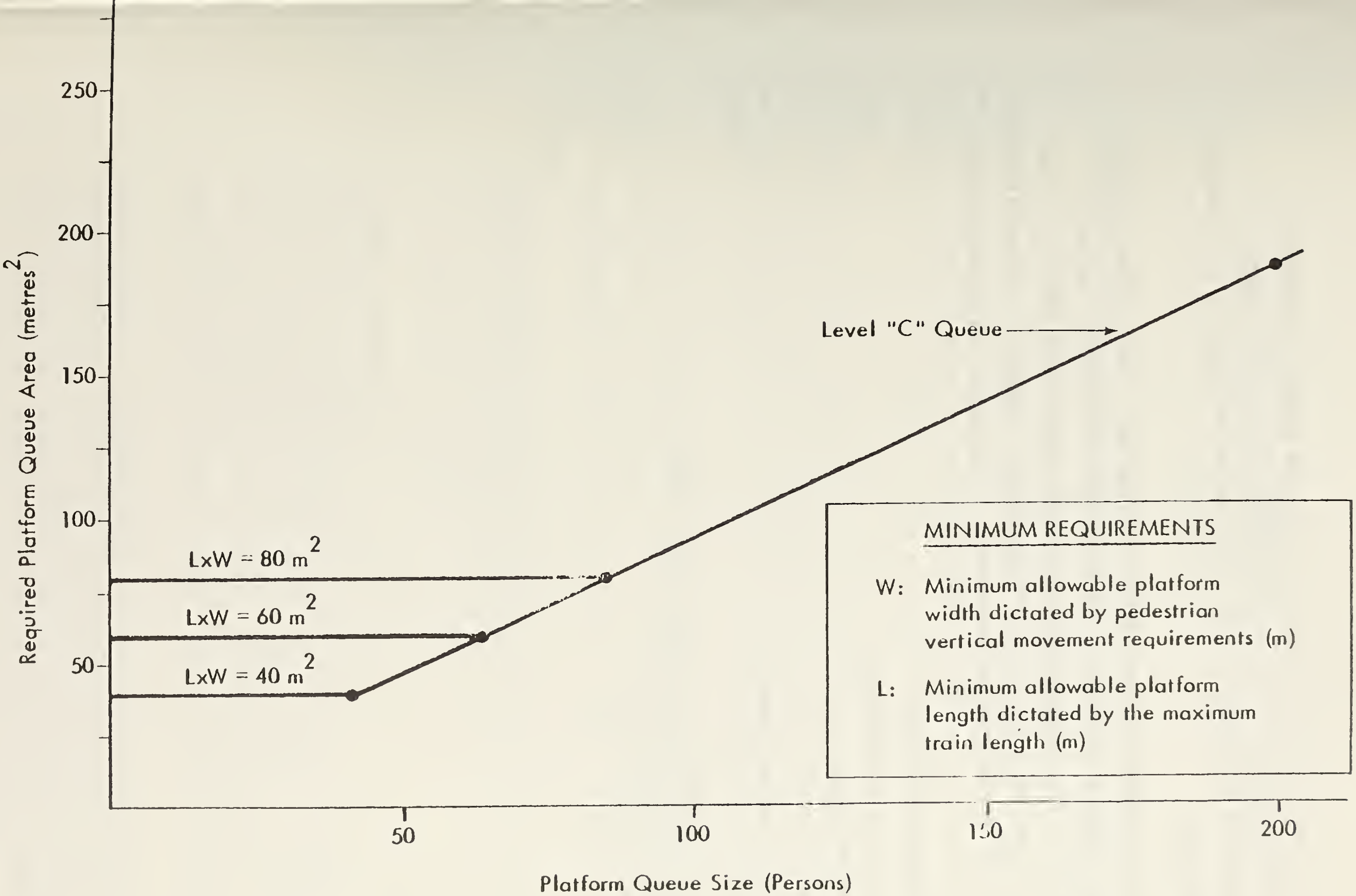


FIGURE D-6. REQUIRED PLATFORM QUEUE AREA AS A FUNCTION OF QUEUE SIZE AND MINIMUM REQUIREMENTS

The last step in this process is to use the System Cost Model to determine the life cycle cost of each station design still under consideration and to choose as the final design that station which exhibits the minimum cost.

In addition to its use as a station sizing tool, the Detailed Station Model can be used to evaluate the flow of vehicles through stations of various designs. Interactions among vehicles and between vehicles at the boarding dock and passengers can be represented in detail. The operation of vehicles on the following types of station links can be represented in the DSM:

- station entry link
- station entry queue(s)
- deboard link(s)
- board link(s)
- station output queue(s)
- station exit link
- vehicle storage and storage access links
- dual mode interface links
- station bypass links

APPENDIX E

COST ANALYSIS

Estimating the costs of a conceptual AGT system deployment is a difficult task which nearly always produces controversial results. It is, therefore, very important that a consistent methodology be employed to generate unit cost and system description estimates for input to a comprehensive model of system costs. During and immediately following the System Operations Studies, an extensive research and analysis effort was undertaken to define a system cost model, a methodology for generating inputs, and a complete set of default input values for the systems evaluated during the SOS program. The purposes of this appendix are to describe the model of system cost which is represented by the current Equation File of the System Cost Model (SCM) and to present the methodology developed to generate SCM input data.

In this appendix the modeling of system costs and the estimating of appropriate input values are described for each major element of system cost. The methodology used to estimate unit cost inputs is summarized as follows:

- Guideway Structure Costs - A methodology to predict unit cost based on total traveling unit mass was developed and may be applied to systems with small consists.

- Guideway Hardware Costs - At this time, there is no differentiation made between systems for the power distribution, snow removal, switching, and wayside control unit cost estimates. Different blocking strategies will, however, allow the analyst to differentiate system complexities by specifying different numbers of control blocks while using the same cost per block for wayside control.

- Vehicle Costs - A representative cost for each system class is estimated based on a nominal vehicle capacity for each class. Variation in cost with vehicle capacity is estimated by straight line interpolation between the values of cost for the nominal

vehicles. Vehicle cost sensitivity to the number of seats, reliability enhancement techniques such as improved quality parts or redundancy, or variations in relative control system sophistication ("smart" vehicles versus "dumb" vehicles) have not been evaluated due to limited reference data.

- Off-Vehicle Control Costs - Consistent with the costing of wayside controls (by block), which allows the modeling of increased network complexity, the central and local station control-hardware costs are estimated for three types of operational control: synchronous, quasi-synchronous, and asynchronous.

- Structures and Equipment Costs - The unit costs used to parametrically model the construction of stations, central control facilities, and feeder garages are taken from the literature. Estimates for the unit costs of AGT maintenance facilities are developed for minimal, medium, and large fleet systems, assuming economies of scale.

- Operations and Maintenance Costs - Labor and parts required to operate and maintain an AGT system are estimated based on parametric quantities such as vehicle-hours, guideway lengths, and fleet size. The methodology is based on the operating and maintenance costs of AIRTRANS, an example of a mature deployment of current AGT technology.

- Non-Vehicle Energy Consumption - The annual energy (BTU/m^2) required to melt guideway snow and to heat and cool the various buildings is estimated for 12 representative cities.

- Energy and Pollution Conversions - The BTU content for various energy sources is listed, along with the cost for each source. The amounts of pollution associated with the use of each energy source is identified from the literature.

- Amortization Factors - The life spans for all capital investments are assumed using UMTA guidelines. Manufacturer's estimates are used to develop a life span for each class of vehicle.

- Inflation and Modification Factors - The price indices for various categories of expense are developed permitting all costs to be corrected to 1977 values.

Future inflation rates are then estimated from these indices. Various other cost factors are also estimated.

E.1 GUIDEWAY STRUCTURE COSTS

The structural cost associated with construction of guideways is intended to exclude the costs of power distribution, communications and control equipment, and snow melting equipment, which are considered separately. Using the data presented in Table E-1 a functional relationship between train mass and guideway unit cost was developed. Such a relationship is useful in modeling one aspect of guideway structural costs (design load) without actually considering a specific design. While the non-structural elements of guideway cost are not used in the development of the relationship, they are included in Table E-1 to show the extent to which the purely structural costs are isolated, or more importantly, to identify those guideway costs which, although used as data points, may still include some non-structural items.

The at-grade and elevated guideway cost data are plotted by vehicle mass in Figure E-1. Inspection shows that the ART system (MARTA) is several magnitudes removed from the other data. Also noteworthy is the observation that the AIRTRANS elevated guideway cost seems to be disproportionately high with respect to the neighboring points.

The physical characteristics of the ten representative system classes of AGT-SOS, and of the five specific data points under analysis, are presented in Table E-2, bearing out the observation drawn from Figure E-1 that ART is

TABLE E-1. GUIDEWAY COSTS

Reference:	(35)	(39)	(40)	(41)	(42)	
$/km	AIRTRANS	GM DM	Rohr DM	TTDDM	MARTA	
at grade	256,400	353,600	252,000	478,500	793,800	Reported Prices
elevated	909,000	661,100	793,750	844,000	1,956,300	
below grade	-	-	-	2,824,400	5,662,500	
power	204,500	none	140,700	309,000	456,250	
snow melt.	-	206,700	-	-		
comm./contrl	350,000	52,000	-	154,200	w/power	
date	1971	1974	1974	1974	1967	
Vehicle Mass (kg)	6350	4865	6704	10,258 *	32,900 *	
at grade	358,600	387,100	275,900	523,900	1,640,800	1975 Corrected Prices
elevated	1,271,250	723,800	869,000	924,000	4,043,700	
below grade	-	-	-	3,092,200	11,704,400	
power	286,000	none	154,000	338,300	943,100	
snow melt	-	226,300	-	-		
comm./contrl.	489,500	57,150	-	168,800	w/power	

* estimated from Classification and Definition report [23]

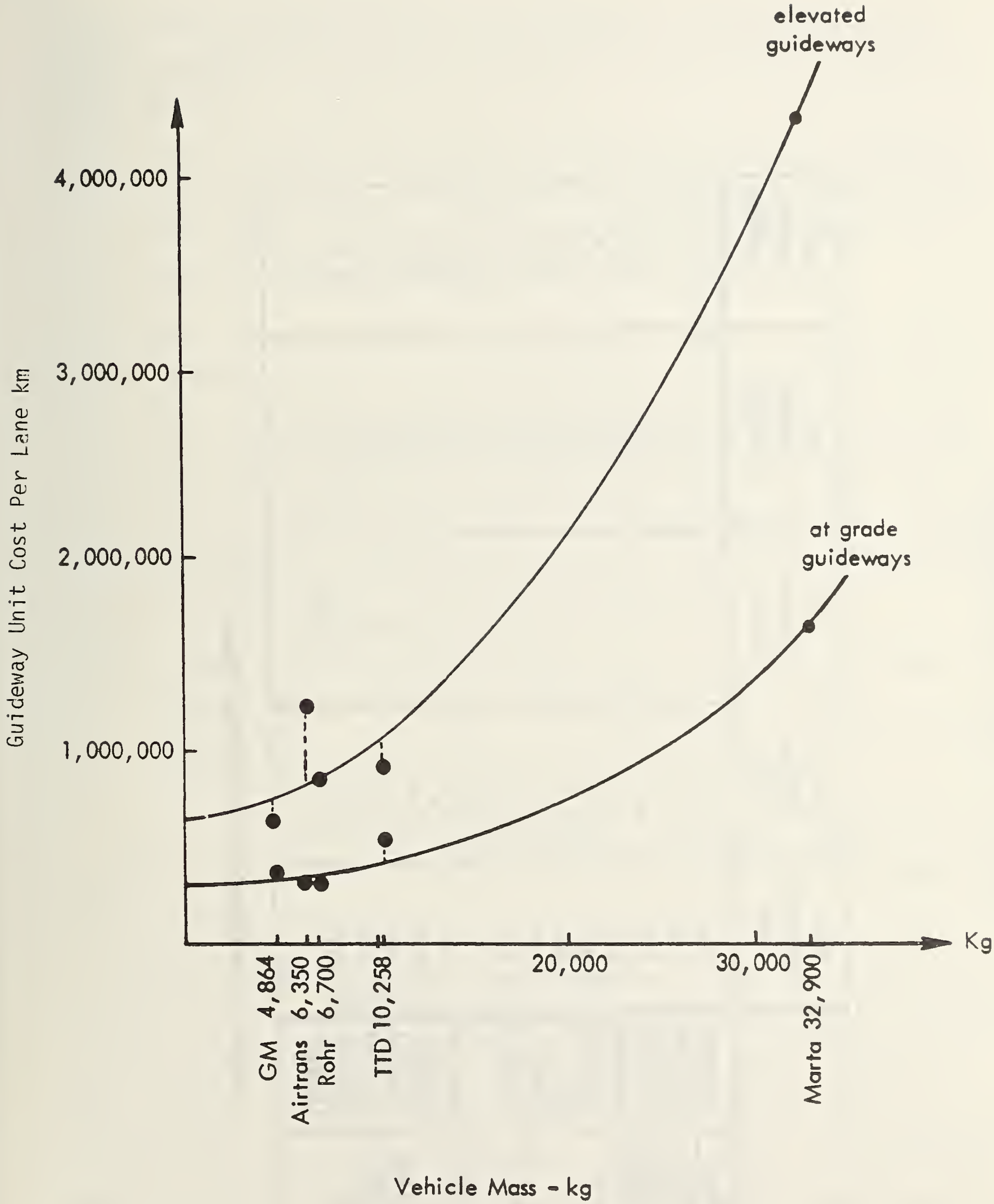


FIGURE E-1. GUIDEWAY UNIT COST VS VEHICLE MASS

TABLE E-2. SYSTEM CHARACTERISTICS

		(Kg) Vehicle Mass	(m) Vehicle Length	(#) Entrain-ment	(m) Vehicle Height	(m) Vehicle Width
PRT-L	nominal	650	2.3	1	1.4	1.3
PRT-H	nominal	770	3.3	1	1.8	1.6
SGRT-L	nominal	3 900	4.7	3	2.7	2.0
SGRT-H	nominal	4 865	8.1	1	2.5	2.4
DMT	nominal	4 865	8.1	1	2.5	2.4
	GM	4 865	8.1	1	2.5	2.4
	Rohr	6 704	8.3	1	2.7	2.4
DMT-P	nominal	10 258	6.9	1	3.5	4.0
		-	6.9	1	3.5	4.0
IGRT-L	nominal	6 349	6.4	4	3.0	2.1
	Airtrans	6 349	6.4	3	3.0	2.1
IGRT-H	nominal	13 500	9.4	6	3.2	2.4
LGRT	nominal	11 600	11.3	2	3.3	2.8
ART	nominal	32 900	23.0	8-10	2.3	3.1
	MARTA	-	-	-	-	-

(Source: Classification and Definition Report [23])

significantly different from the other systems. In factors that would affect guideway design and cost, ART differs from GRT and PRT systems in these respects:

- It is the only one of the ten classes which employs a steel-wheel, steel-rail track. The extra cost for "trackage" is reported to be \$256,250/km in 1967 dollars for MARTA.[42] This cost alone is as much as some total guideway costs for GRT systems.

- While the range of train lengths for PRT and AGT systems is 2-57 meters, ART trains may be up to 230 meters long (10 vehicles @ 23 m). Considering a typical elevated span of 100 feet (about 30 m), this implies a different dynamic loading. ART trains will extend over several spans while most GRT systems will have small or one vehicle consists applying what is relatively a point load. Headway separations are generally great enough to prevent more than one GRT vehicle (or train) from loading a given span.

- The ART vehicle mass and guideway costs are so much larger than those of GRT systems that a large gap would be left to interpolation. This places an artificially high weighting on this (ART) point in any statistical analysis of the data.

Thus, a design for an ART system guideway is different enough to warrant separate consideration. This data point is not used in the development of the cost-mass relationship.

The data in Table E-2 also reveals that the AIRTRANS data point may not be too high (Figure E-1), but rather that it is not far enough to the right, for the AIRTRANS traveling unit may consist of three vehicles while the other systems' vehicles cannot be entrained. After eliminating ART and moving AIRTRANS, the data points are plotted in Figure E-2. The lines drawn are least squares regression fit of the four data points, but because the sample size is not statistically significant, justification must be made on other grounds.

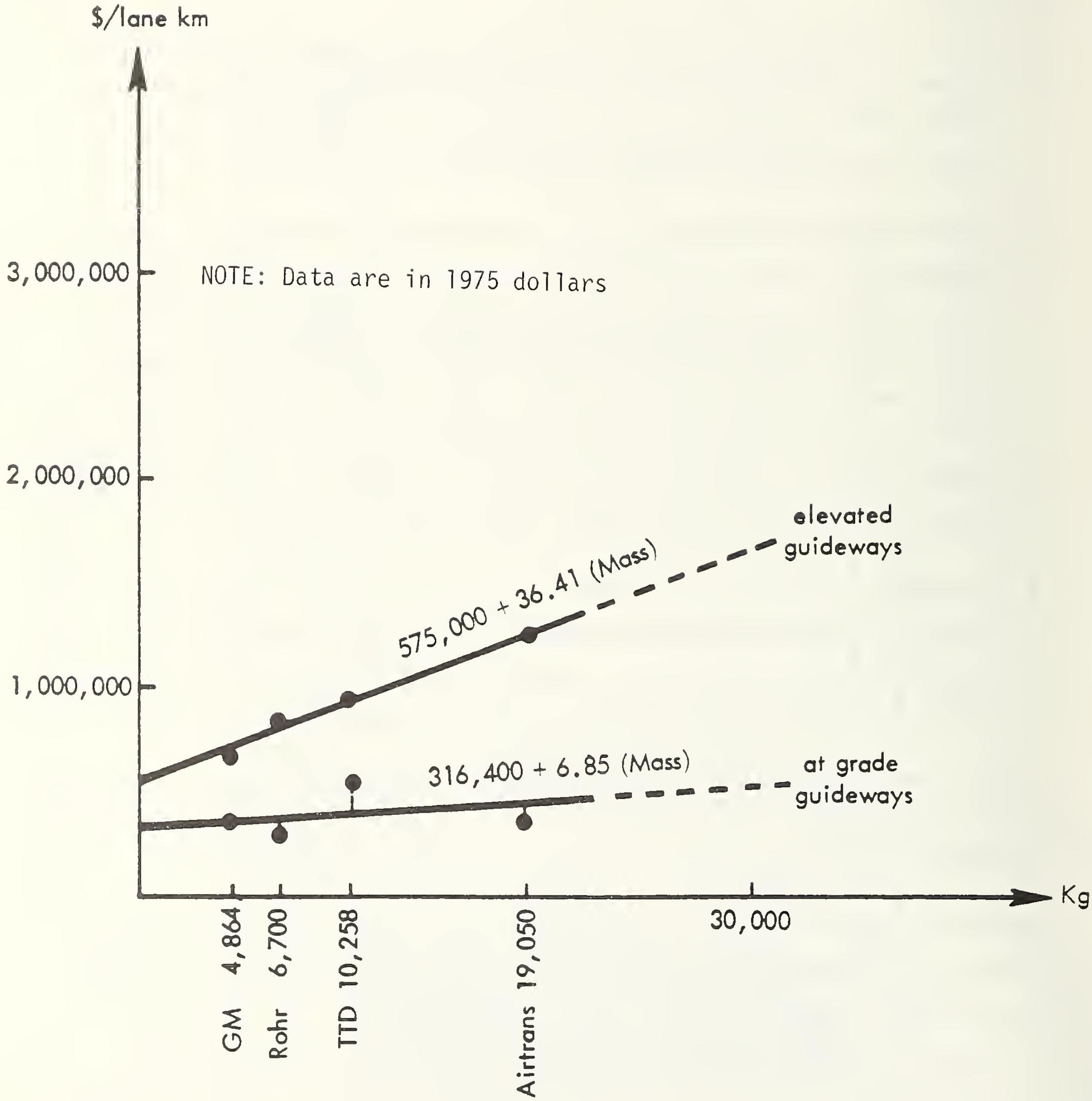


FIGURE E-2. GUIDEWAY UNIT COST VS TRAIN MASS

Figure E-3 shows the change in unit costs for highway bridges as designed for either a 15 ton (13 500 kg) or 20 ton (18 000 kg) vehicle, as per Gurski.[43] Each pair of points connected by a line represents one of three different structural designs (concrete box girder; prestressed concrete girder; welded steel girder), or a different simple span length for one given design type. The four circled points in this figure are GM Dual Mode System estimates,[39] which are indeed consistent with Gurski's analysis. Thus, the following observations provide a basis for substantiating the relationship developed for guideway unit cost as a function of train mass:

1. The relationship is consistent with the preconceived notions that increasing train mass results in increased guideway costs (the elevated guideway costs in fact increase monotonically with increasing train mass) and that this effect is more pronounced when the guideway is elevated.

2. While the amount of data is very limited, the derived relationship does fit the available data quite well.

3. Both the magnitude of the cost and the rate of increase in cost with train mass are consistent with other research on elevated guideway costs.

For below-grade guideways the cost is assumed to be that of an at-grade guideway plus the added cost of all the excavation work, taken from the one GRT data point for below-grade guideways (see Ref. 41). It has been shown that for modest variations in diameters of tunnels (3 to 4 1/2 meter range), the differences in cost are marginal. Rather, it is the materials used, methods employed, and ground type excavated which determine cost of tunnelling (all of which can be assumed to be constant for all systems of study in a particular application area).

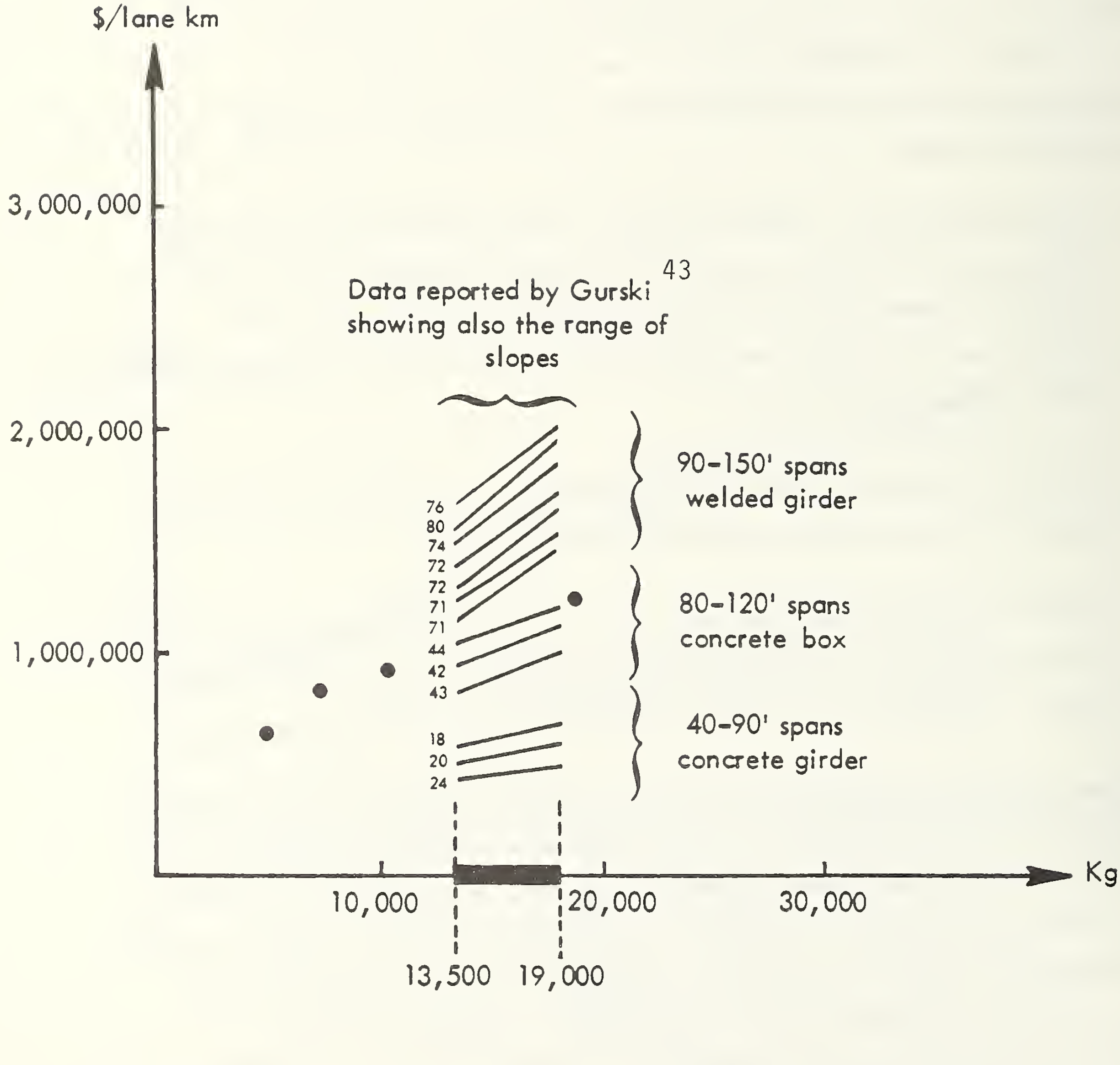


FIGURE E-3. BRIDGE UNIT COST VS DESIGN LOAD
(various designs and span lengths)

The relationships used to estimate guideway structure costs for PRT, GRT (including SLT deployments), and ART systems are as follows (in 1975 dollars):

Type		PRT and GRT	ART
at-grade ($/km)	=	316,400 + 6.85 (M)	1,640,800
elevated ($/km	=	575,000 + 36.41(M)	4,093,700
below-grade ($/km)	=	3,021,900 + 6.85 (M)	11,704,400

where M = Mass of an empty train in kilograms

The total cost of guideway structures is calculated by the System Cost Model (SCM) as the product of a user input unit cost per lane kilometer and the number of lane kilometers of at grade, elevated, and below grade guideway in the network. To account for cost savings which might accrue from the construction of one kilometer of dual lane guideway versus two kilometers of single lane guideway, the SCM applies a user defined factor to the unit cost estimates if dual lane guideway is specified. The SCM applies another user defined factor to guideway unit cost to account for the impact of increased disruption associated with construction within urbanized areas.

E.2 GUIDEWAY HARDWARE COSTS

The hardware equipment associated with guideways includes the power distribution system, switching equipment, a snow-melting system, and wayside communications and control. The costs for power distribution on various systems is shown in Table E-3. The linear average is $298,500, which can be taken as an adequate representative cost that compares reasonably well with power costs of the three displayed systems. Table E-4 shows the costs for switching mechanisms on the AIRTRANS [35] and proposed GM Dual Mode [39] systems.

In isolating the causes of increased cost for wayside communications and control, Table E-5 shows the costs per kilometer for four systems. The Monocab PRT is the most costly, as would be expected because of the

TABLE E-3. POWER DISTRIBUTION INSTALLATION COSTS

System	Date	Value ($/km)	1977 Value	Reference
AIRTRANS	1971	204,500	286,647	35
Rohr	1974	140,700	172,780	40
TTD	1974	309,000	379,452	41
Cabinentaxi	1977	100,000	100,000	23
BART	1972	147,980	205,751	23
Mini/MonoRail	1975	432,840	472,218	23
NTS	1976	450,000	469,898	23
VONA	1975	180,000	196,375	23
Monocab	1975	370,000	403,660	23

TABLE E-4. EXTRA COST FOR SWITCHING

System	Date	Value ($ each)	1977 Value	Reference
AIRTRANS - diverge	1971	15,600	21,842	35
AIRTRANS - converge	1971	14,939	20,942	35
GMDM - diverge	1974	51,000	62,628	39
GMDM - converge	1974	52,744	64,770	39
GMDM - elevated div.	1974	77,240	94,851	39
GMDM - elevated conv.	1974	79,000	97,012	39

TABLE E-5. WAYSIDE CONTROL/COMMUNICATIONS COST

System	Date	Value ($/km)	1977 Value	Reference
Airtrans	1971	206,381	289,310	35
GM Dual Mode	1974	52,000	63,856	39
TTD Dual Mode	1974	154,200	189,358	41
Monocab PRT	1975	680,000	741,862	23

extensive decision-making required, but the simplest system of the sample, AIRTRANS, is not the least costly. If the data are to be believed, this might indicate that while the TTD and GM systems require more sophistication (more decision points), one can take advantage of the distance between such points in specifying larger block sizes. Thus, a better indicator of cost for wayside electronics might be the number of blocks required. From Airtrans data [35] this cost is about $6,690,000 for about 759 blocks, averaging $6,179 per block, in 1971 dollars. Applying this figure to a separate methodology for determining the number of blocks required in a system deployment could account for increased complexity and was selected as a cost estimating technique in this analysis. The required number of blocks can be estimated using the methodology given in Appendix C (Section C.3).

The cost for installation of a system for snow and ice removal is taken from the study performed [44] during the GM Dual Mode project, and models a hot fluid system. (Imbedded electrical heating and infrared radiant heating were also considered in the study, but they were rejected in favor of the hot fluid system on the basis of minimum life cycle cost.) The cost is $206,700 per km in 1974 dollars or $271,400 when corrected to 1977 values (for a 3 meter width).

Thus, the following estimates are derived (in 1977 dollars):

CPOW = Cost of power distribution system installation	=	$298,500/km
CWCC = Cost of wayside communications and control	=	$8,662/block
CSNW = Cost of snow melting system installation	=	$90,500/km per m width

The SCM calculates the total capital cost of the guideway as the sum of structural cost, wayside communication and control cost, and snow melting system cost. The installation cost of the power distribution system is calculated and reported separately.

E.3 VEHICLE COSTS

The costs for various AGT vehicle types are accumulated in Table E-6. The costs and dates of quotes are extracted from the data tables in the appendix to the SOS Classification and Definition Report.[23] The costs are each corrected to reflect the 1977 value, according to the inflators to be

TABLE E-6. AGT VEHICLE COSTS

Class	Name	Date	Cost	Individual 1977 Costs	Representative 1977 Cost
PRT-L	1 Cabinentaxi*	1976	$33,000	36,686	37,000
	2 Aramis	1976	24,000	26,680	
PRT-H	3 CVS (4,000 veh.)	1976	17,000	18,900	58,000
	4 Monocab (140 veh.)	1975	80,000	94,592	
SGRT-L	5 Morgantown*	1976	150,000	166,000	167,000
SGRT-H	---	---	---	---	167,000
DMT	6 GMDM	1974	36,355	52,801	46,000
	7 Rohr DM	1974	25,750	37,400	
DMT-P	8 TTI w/Pallet	1974	115,000	167,024	168,000
IGRT-L	9 Unimobil II	1976	25,000	27,792	238,000
	10 WEDway	1976	7,200	8,000	
	11 Rohr "P"	1976	225,000	250,123	
	12 Airtrans*	1976	213,500	237,344	
IGRT-H	13 Dashveyor	1976	125,000	138,968	238,000
	14 NTS	1976	120,000	133,400	
	15 Project 21	1976	100,000	111,162	
	16 Transurban	1976	92,500	102,831	
	17 Aerotrain	1976	200,000	222,336	
	18 VONA	1975	80,000	94,592	
LGRT	19 Westinghouse	1976	400,000	444,673	445,000
ART	BART	---	339,000		800,000
	Rohr "N"	1976	63,000	70,036	
	WMATA	1975	305,000	360,634	
	APTA*	1977	800,000	800,000	

*These systems represent costs for deployed systems and are considered dominant.

used as input to the SCM (in this instance, the wholesale price index of railroad equipment, extrapolated after 1976). For each class of system, a representative 1977 cost is estimated (by rounding up to the nearest thousand) from either the dominant value in that class or a linear average of all costs for that class. A constraint that a high speed vehicle cannot cost less than a similar low speed vehicle is also assumed. The data listed in Table E-6 are plotted in Figure E-4. Without considering specific vehicle design, the data indicate a distinct increase in cost with increasing vehicle capacity. While other factors surely influence cost, it is assumed in this analysis that vehicle size is a major contributor. The data generally verify this conclusion. Therefore, in order to account for the effects on vehicle cost of variations in vehicle capacity within each system class, straight-line interpolation is used between the values of cost for the representative vehicle within each class. The vehicle capacity and cost of the representative vehicles are summarized in Table E-7. The nominal capacity of each representative vehicle was selected based on the characteristics of other vehicles in the class as reported in the Classification and Definition report.[23] The incremental vehicle costs per passenger resulting from interpolation are presented in Table E-8. The choice of point to point interpolation relies only on immediately neighboring points for additional information reducing generality and retaining the dominant data points as part of the line.

A 17-passenger feeder bus (demand responsive, demand subscription) is assumed to cost $21,000 in 1976 dollars,[45] and a 52-passenger feeder bus (fixed route) is assumed to cost $60,000 in 1976 dollars on a linear average of 14 cities.[46]

The SCM calculates the cost of the vehicle fleet simply as the product of vehicle cost for each vehicle and the number of vehicles in the fleet including spares. The number of AGT vehicles in the active fleet is specified as a result of trade-off analysis using the DESM. The number of spare vehicles required to assure that a stand-by vehicle will be available in the event of an active fleet vehicle failure is determined by the System Availability Model (SAM). The Feeder System Model (FSM) estimates the size of the feeder bus fleet.

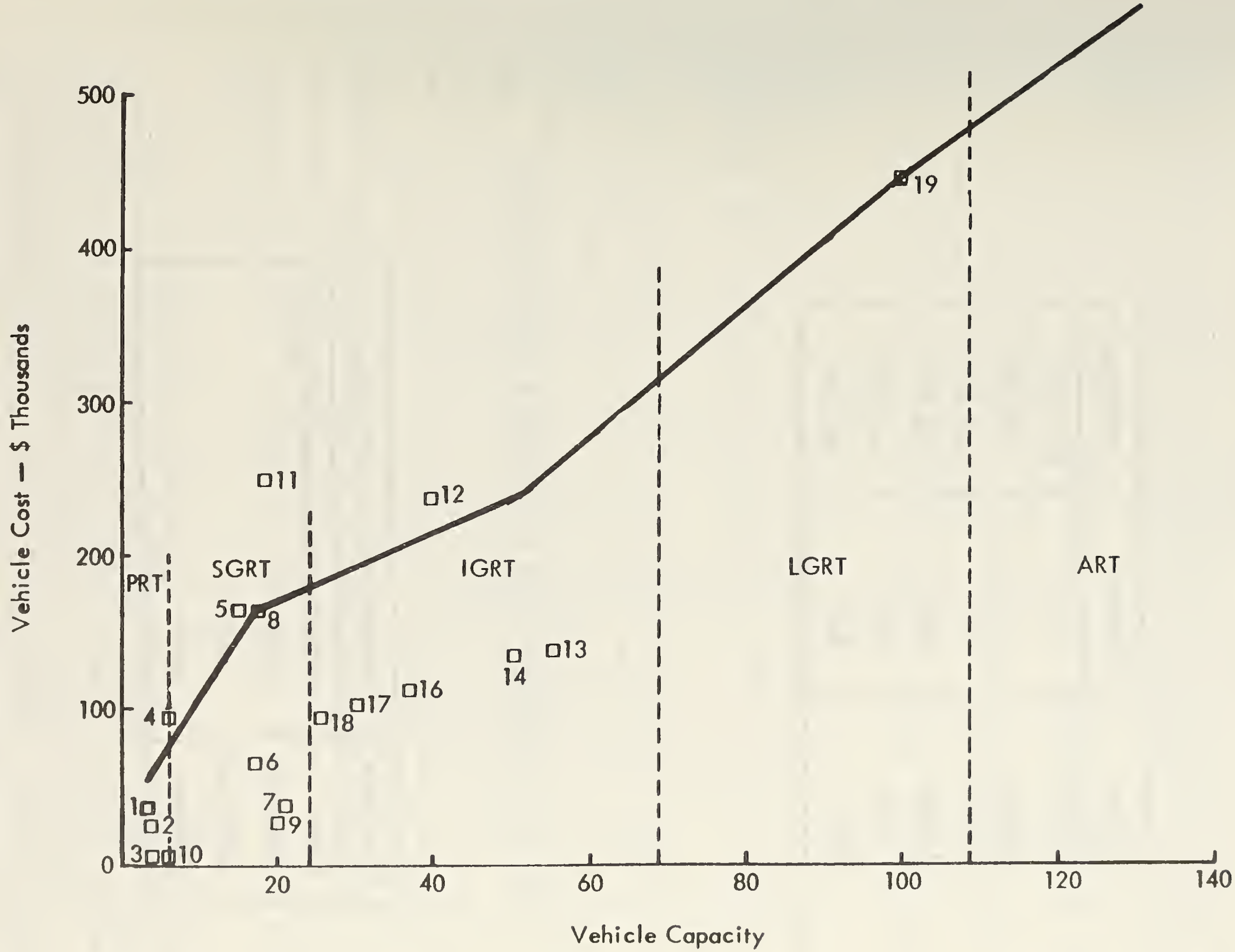


FIGURE E-4. VEHICLE CAPITAL COST VERSUS VEHICLE CAPACITY

TABLE E-7. CAPACITY AND COST OF REPRESENTATIVE AGT VEHICLES

Class	Capacity	1977 Cost
PRT-l	4	$ 37,000
PRT-h	4	58,000
SGRT	17	167,000
IGRT	50	238,000
LGRT	100	445,000
ART	200	800,000

TABLE E-8. INCREMENTAL COSTS PER PASSENGER FOR AGT VEHICLES

Class Range	Incremental Cost (1977 dollars)
SGRT	$8385/additional passenger capacity
SGRT-IGRT	2152
IGRT-LGRT	4140
LGRT-ART	3287

E.4 OFF-VEHICLE CONTROL COSTS

The estimates of control system costs originally developed in the System Operation Studies differentiated system complexity based on the network characteristic (shuttle, branch, grid). A further refinement is to consider the actual control rationale:

1. Asynchronous control, where vehicles are launched when ready and resolve any conflicts en route
2. Quasi-synchronous control, where vehicles are launched so as to reduce potential interactions
3. Synchronous control, where each vehicle's motion is predetermined from start to finish

The specification of any one of these control types has a direct impact on the Launching Strategy, the Vehicle Movement Control, and the Merging Resolution [19], as designated in Table E-9.

Table E-10 lists the primary functions of the physical components of any control system [19,47], which are the items for which a cost value is estimated. Note that three of these components (central, wayside/sector, and switch) are impacted by the various control alternatives identified in Table E-9, and that separate unit costs need to be estimated for the alternative control strategies of each component. A single unit cost is needed for the Station Control component since it is chiefly unaffected by the control alternatives. On-board Vehicle Control cost, while it is dependent upon control strategy, is not required separately from the entire vehicle cost for use in the SCM, and is thus not estimated here. Caudill, Kornhauser, and Wroble [47] estimate this value to be in the range of $825 - $1625 per vehicle.

Table E-11 presents data on control system costs for three AGT systems, one of each control type (Asynch, Quasi-synch, Synch). For lack of more complete data, it was assumed that the cost of merge resolution equipment at switches is zero for synchronous control, and that quasi-synchronous switching equipment costs are the same as asynchronous. The unit cost for the wayside/sector control equipment is assumed to be independent of control

TABLE E-9. CONTROL STRATEGIES IMPACTING COST

ASYNCH.	QUASI-SYNC	SYNCH.		UNIT COST
			LAUNCH STRATEGIES (CENTRAL)	
		X	DETERMINISTIC	$/SYSTEM
X	X		NON-DETERMINISTIC	$/SYSTEM
			VEHICLE MOVEMENT CONTROL (WAYSIDE/SECTOR)	
	X	X	POINT FOLLOWER	$/BLOCK
X			VEHICLE FOLLOWER	$/BLOCK
			MERGE RESOLUTION (SWITCH)	
X			LOCAL MERGING	$/SWITCH
	X		WINDOWED MERGING	$/SWITCH
		X	PRE-PLANNED MERGING	$/SWITCH
			IN-STATION CONTROL (STATION)	
X	X	X	PLATFORM APPROACH CONTROL	$/PLATFORM

TABLE E-10. AGT COMPONENT CONTROL HIERARCHY

COMPONENT	GENERAL FUNCTION	SPECIFIC FUNCTIONS
Central Control	Global Interface and System Management Signal Generation	• Vehicle Pathing • Vehicle Launching • System Monitoring • Empty Vehicle Management
Wayside/Sector Control	Command Signal Generation and Information Relay	• Vehicle Velocity/Position Profile • Collision Avoidance – Line Haul • Vehicle Sensing and Commanding
Switch Control Equipment	Interpretation, Processing, and Generation of Merge/Diverge Signals	• Collision Avoidance – Merge • Conflict Resolution – Merge • Conflict Resolution – Diverge
Station Control Equipment	Start/Stop Signal Generation and Vehicle Routing Information Relay	• Platform Approach Profiles • Platform/Berth Selection • Queueing Resolution
Vehicle On-Board Control	Interpretation and Compliance with Command Signals	• Longitudinal Control Compliance • Lateral Control Adherence • Collision Reaction (Brake Profile)

TABLE E-11. CONTROL SYSTEM COST VALUES

St. Paul[77] (Asynch)	AIRTRANS[35] (QuasiSynch)	Morgantown[23] (Synch)		RECOMMENDED SCM VALUE	
		—	DETERMINISTIC	$2,976,462	CENTRAL CONTROL (CCEQ)
$827,935	—		NON-DETERMINISTIC	$827,935	
	$8662/block	—	POINT FOLLOWER	$8662/block	WAYSIDE CONTROL (CWCC)
$261,906/km			VEHICLE FOLLOWER	$8662/block	
$10,720/sw			LOCAL MERGE	$35,720/switch	SWITCH EQUIPMENT* (CSWML)
	—		WINDOWED MERGE	$35,720/switch	
		—	PRGPLANNED MERGE	$25,000/switch	
$23,090/stn	—	—	PLATFORM APPROACH	$23,090/platform	STATION CONTROL EQUIP. (CSTEQ)
-	$7,860,000	$5,075,000	Total Control Cost (1978 $)		
8.8 km	20.5 km	6.7 km	Guideway Length		
40	71	16	Number of Switches		
14	14	6	Number of Platform Lanes		

*NOTE: Switch equipment includes the control electronics and $25,000 for mechanical hardware as per the St. Paul System.

strategy, but the number of control blocks specified can be used to differentiate between a point-follower and vehicle-follower system, if necessary. The central control cost for a deterministic system was derived from taking the total control cost for Morgantown and subtracting out the appropriate component costs. For this calculation, the total cost was first updated to an equivalent 1978 value, and the AIRTRANS wayside/sector control estimate ($8662/block) was converted to its unit length equivalent ($292,537/lane kilometer).

A facility to house the central control equipment should also be considered in the cost of the off-vehicle control system. Depending on the complexity of the control system and the extent of the network, a building of from 200 m^2 to 800 m^2 should be included. The area of the central control building is defined in the SCM input as the variable CNABLD.

In order to assess the validity of these estimates for control system costs, they were applied to three operational systems of known total control cost, with the following results:

System	Actual Control Cost	Estimated Control Cost	Error
Tampa [48]	$1,647,954	$1,773,568	8%
Sea-Tac [49]	$2,870,040	$1,719,801	-40%
Fairlane [50]	$ 944,640	$1,105,080	17%

It should be noted that all of these three are simple shuttle or loop networks and thus assumed to be controlled by asynchronous strategies.

The Sea-Tac system is known to include extensive central control equipment for monitoring system status and to recover from network blockages [49]. These functions are beyond what was estimated here, and thus the Sea-Tac estimation error is anticipated. Other variations in central control costs not explicitly studied here include: Scheduling of service, routing between stations, and pathing along links. The costs of these higher order functions should be added to the current estimates when more than the trivial case of each is to be assumed.

The SCM calculates the cost of off-vehicle control as the sum of the central control building cost, the central control equipment cost, and guideway switch equipment cost. The cost of wayside control is included in the cost of the guideway, and the cost of station control equipment is included in the station cost.

E.5 STRUCTURES AND EQUIPMENT COSTS

The major structural costs and the major equipment costs of an AGT network are estimated in Tables E-12 and E-13, respectively. These values are first-cut estimates which were used in determining input values for the SCM. The mnemonic name of the appropriate input parameter is identified for each estimate. An estimate may be in the form for direct input or may consist of a "rule of thumb" specifying alternative values and methods for estimating the direct input. Costs and floor areas of the maintenance facilities are specified separately in the following paragraphs.

The parametric design of the maintenance and operating garages is dependent on two factors: unit cost of the structure and unit area required for the vehicles. Statistics from 4 bus garages and 2 AGT vehicle garages are displayed in Table E-14, all as representative maintenance facility characteristics (ART may not fit into this scenario) for typical AGT systems. The computed cost per unit area shows two clusters of data: 5 values near $\$30/ft^2$ and 2 values near $\$60/ft^2$. The five less expensive estimates are taken as adequate representative costs. The computed area requirements show three clusters of values: a unit area for heavy maintenance (per vehicle in the shop), a unit area for operating garages (per vehicle in the fleet), and a unit area for operating and storage garages.

These values, however, are representative of unit cost and area for large systems. According to SEMTA data [45] garage area is about 12.6 m^2/veh. in fleet and about 180 m^2/veh. in shop. This value is used for smaller systems (up to 200 vehicles). A minimum of 2 stalls is assumed at 646 ft^2/stall (from Table E-12), resulting in 116 m^2. This approach

TABLE E-12. MAJOR STRUCTURAL COSTS (Excluding Guideways)

Mnemonic	Units	Description	IANDD file	Estimation	Reference
CFGAR	\$/veh.	Cost – Feeder Maint. Bldg.	.SCMCOM	\$5600/veh.	45 – 1976
CFSER	\$/veh.	Cost – Feeder Stor. Bldg.	.SCMCOM	\$2200/veh.	45 – 1976
CSTBLD	\$/m^2	Cost – Station Bldg.	.SCMCOM	\$387/m^2 CBD \$369/m^2 other	39 – 1974 39 – 1974
CPRK	\$/space	Cost – Station Parking	.SCMCOM	\$262/space	51 – 1971
STAPRK	space/patron	Area – Station Parking	.SCMCOM	$1/1.3$	52
CCNBLD	\$/m^2	Cost – Control Bldg.	.SCMCOM	\$392/m^2	39 – 1974
CNABLD	m^2	Area – Control Bldg.	.SCMDPLY	810 m^2 400 m^2 200 m^2	large network small network nominal network
FAGAR	m^2/veh.	Area – Feeder Maint. Bldg.	.SCMCOM	12.6 m^2/veh.	45
FASER	m^2/veh.	Area – Feeder Stor. Bldg.	.SCMCOM	20.3 m^2/veh.	45

TABLE E-13. MAJOR EQUIPMENT COSTS (Excluding Vehicles)

Mnemonic	Units	Description	IANDD File	Estimation	Reference
CFMEQ	$/veh.	Cost - Feeder Maint. Eq.	.SCMCOM	Included in CFGAR, CFSER	
CGAREQ	$/veh.	Cost - Maintenance Eq.	.SCMSYS	$112/veh.*	45 - 1974
CSEREQ	$/veh.	Cost - Operating Garage Eq.	.SCMSYS	$460/veh.*	39 - 1974
CSTICK	$ each	Cost - Ticket Machine	.SCMCOM	$15,000	39 - 1974
CSTDR	$ each	Cost - Platform Doors	.SCMCOM	$9,000	39 - 1974
CSTTRN	$ each	Cost - Turnstiles	.SCMCOM	$12,000	39 - 1974
CSTVM	$/station	Cost - Vertical Movement	.SCMCOM	$50,000/elevator $40,000/escalator	39 - 1974
CSTDM	$/station	Cost - Dual Mode Electronics	.SCMDPLY	$71,200/station 2 bays, 78 parking	39 - 1974
CFEQ	$	Cost - Feeder Demand Responsive Equipment	.SCMDPLY	UHF: $1252/mi^2 $ 4650/station Radio: $25/peak hour veh $5000 Phones: $25/peak hour pass.	39 - 1974

*These values are for large systems; a minimum of $40,000 should be used as a total.

TABLE E-14. MAINTENANCE FACILITY STATISTICS

Garage Type	Cost ($)	Area (ft^2)	# Stalls	# Vehicles	Source	$/$ft^2$	ft^2/veh
Maintenance	1,353,870 (1,102,500)	50,400	78	162 (in shop)	ref. 39	26.86	311 (646 per stall)
Operating	(479,000)	18,300	20	387 (fleet) (2319 ÷ 6)	ref. 39	32.14	47.3
Operating	---	11,000	---	254 (fleet)	ref. 53	---	43.3
Operating w/Storage	---	160,000	252 (storage)	---	ref. 54	---	635
Operating w/Storage	---	139,860	240 (storage)	---	ref. 55	---	583
Combined	7,200,426 (6,600,000)	256,000	---	---	ref. 54	28.13	---
Combined	2,600,000	83,000	---	---	ref. 56	31.33	---
2 - Buildings	4,000,000	58,000	---	---	ref. 53	68.97	---
2 - Buildings w/Storage	9,500,000	172,910	---	---	ref. 55	54.94	---
Combined	---	---	---	---	ref. 40	30.70 (25.00)	---

*All dollars are corrected to 1977 values; numbers in parentheses are original reported costs.

assumes that the discrepancies in the data on garage area are due to the difference in system size (several hundred vehicles versus several thousand), resulting in distinct economics of scale. At the low end, a minimal number of stalls is required to handle certain types of maintenance functions, although the stalls may not always be in use. At the high end, the maintenance schedule of thousands of vehicles will more likely smooth out to a more uniform usage of all stalls (thus needing fewer per vehicle). Thus, the estimates for garage area are:

	Minimum Area	Medium Size (up to 200 veh.)	Large Size (over 1000 veh.)
MTAGAR - Area of maintenance garage	116 m^2	12.6 m^2/veh. in fleet	28 m^2/veh. in shop
MTASER - Area of operating garage	4 m^2/veh.	4 m^2/veh. in fleet	4 m^2/veh. in fleet

and the cost is assumed to be:

CSER, CGAR = $\$29.83/ft^2 = \$330/m^2$ where CSER and CGAR are the cost per square meter of the operating garage and the maintenance garage, respectively.

E.6 OPERATIONS AND MAINTENANCE COSTS

The rationale introduced in the first-cut estimation of operational labor during the System Operations Studies involved the estimation of labor requirements, salary levels, and maintenance parts. This process was not, however, included as part of the cost tree in the SCM, and therefore, this computation burden fell upon the user during input preparation. In light of increased disaggregate data on operating and maintenance labor for the AIRTRANS system [57], this rationale has been formalized as part of a new version of the SCM cost tree.

The basic form of these computations is as follows:

$$\begin{pmatrix}\text{Unit Labor}\\\text{Required}\end{pmatrix}\begin{pmatrix}\text{System}\\\text{Parameters}\end{pmatrix}\begin{pmatrix}\text{Labor}\\\text{Rate}\end{pmatrix}+\begin{pmatrix}\text{Unit Materials or}\\\text{Services Required}\end{pmatrix}\begin{pmatrix}\text{System}\\\text{Parameters}\end{pmatrix}$$

The system parameters are measures of system operation such as system-hours, vehicle-kilometers, or guideway length. The unit labor requirements and unit materials/services are parametric estimates to be stored in the common file for continued use in the SCM and should be independent of system type or deployment. Similarly, the labor rates are to be estimated once and stored for continual use as parametric quantities. This change, therefore, involves the addition of more input for the common file, but the elimination of other values in the deployment and system files; a net decrease in the amount of information to be supplied by the user from run to run.

Table E-15 lists the categories of labor and Table E-16 lists the categories of parts which were developed as parametric estimates of AGT operations/maintenance, in addition to the estimated values. Table E-17 shows the labor rates, estimated from Airtrans salaries [57], assuming a 1.2 overhead factor and 1880 hours of work per year.

In order to assess the validity of these estimates, the actual operations and maintenance costs for a year of operations for five AGT systems are compared to the estimated value in the following table:

System	Actual O & M Cost	Est. O & M Cost	Error
Kings Dominion [58]	$ 139,500	$ 168,202	21%
Houston Airport [59]	304,330	470,101	54%
Fairlane [50]	340,000	178,258	-48%
Seattle-Tacoma [49]	743,000	655,838	-12%
Tampa [48]	421,980	500,958	19%

TABLE E-15 AGT LABOR REQUIREMENTS

	Airtrans [57] (hours)	Unit Requirement per year of operation	Labor Type
System Operators	17,520	2.0 mh/hr	Operator
Station Attendants	71,073	0.5795 mh/st/hr	Attendant
Maintenance Supervision	47,347	0.2574 mh/km/hr	Supervisor
Central CCC Maintenance	5,511	0.6291 mh/hr	Technician
Wayside CCC Maintenance	9,776	0.0544 mh/km/hr	
Switch Maintenance	4,886	0.0079 mh/sw/hr	
Door Maintenance	1,764	0.0072 mh/each/hr	
Fare Device Maintenance	5,529	0.0137 mh/each/hr	
Security Equipment Maintenance	1,277	91.2 mh/st	
Garage Equipment Maintenance	1,589	40.7 mh/veh	
Guideway/Power Maintenance	14,986	731.0 mh/km	
Snow System Maintenance (14)	-	13.1 mh/km	
Vehicle Maintenance	51,636	0.0092 mh/vkm	Mechanic
Vehicle Preparation	17,446	0.0511 mh/veh/hr	

TABLE E-16. AGT MATERIALS/SERVICES

	Unit Cost [57]
Building Maintenance	$6.67/sq.m.
Vehicle Parts	$0.0932/vkm
Guideway Parts	$8250/lane km
Snow System Parts (14)	$5080/lane km
Electronics Parts	0.0153 $/$ Capital Cost
General Adm. Service	0.0213 $/$ Oper. Maint.

TABLE E-17. AGT LABOR RATES

	Airtrans [57]	Unit Cost
Operator	$14,580	$9.31/mh
Attendant	8,285	$5.29/mh
Supervisor	14,482	$9.24/mh
Technician	12,190	$7.78/mh
Mechanic	12,190	$7.78/mh

E.7 ENERGY CONSUMPTION

The energy consumption not directly associated with AGT vehicle propulsion includes that required for the guideway weather protection system, the feeder vehicle propulsion, wayside communications and control operation, and the heating, cooling, and electrical requirements in all buildings and garages.

If the process is automated, a reasonable guideway weather protection system would typically be one of three types:

- Circulating hot fluid in embedded pipes
- Embedded electric heating resistance cable or wire
- Overhead high intensity infrared radiant energy

In order to cost and to estimate the energy required for a snow and ice melting system, one of these design types should be assumed. Consistent with conclusions reached in the GM Dual Mode Study [44], a circulating hot fluid system is assumed.

In estimating the energy required to melt and remove snow from the guideway, two processes must be analyzed: a mass transfer due to evaporation and a heat transfer by convection and radiation. "Chapter 38: Snow Melting" in the ASHRAE Handbook and Product Directory, Systems Edition[60] provides an excellent analysis of the energy required to melt snow on sidewalks, runways, roads, and ramps. The heat required to melt and evaporate the snow is a function of snowfall rate and wind velocity, respectively, and the heat transferred to the snow and to the air is additionally a function of temperature and humidity. Thus, by examining these climatic factors in different cities and integrating throughout a typical year in each city (snowfall and associated wind, temperature, and humidity value frequencies), estimates can be derived for the energy required to meet a given statistical criterion. The energy required for a Class II snow melting criterion (commercial) is listed in Table E-18 for 9 of the 33 cities examined in the analysis [60]. These were chosen because they adequately represent a cross section of U.S. climate types, and the data can be paired with available data on other types of energy

TABLE E-18. SNOW MELTING ENERGY

City	Annual Energy Output		Supplied at 70% eff. BTU/m^2
	BTU/ft^2	BTU/m^2	
Miami	0	0	0
Los Angeles	0	0	0
Albequerque	30,069	334,100	477,286
Denver/Colorado Springs	103,960	1,155,111	1,650,159
Dallas/Ft. Worth	0	0	0
Memphis/Nashville	15,221	169,122	241,603
Washington, D.C.	25,260	280,666	400,952
Salt Lake/Ogden	81,170	901,889	1,288,413
Seattle	8,180	90,889	129,841
Boston	64,486	716,444	1,023,492
Chicago	133,390	1,482,111	2,117,302
New York	82,390	915,445	1,307,778

requirements. The values represent the output requirements, so an efficiency factor for the system must be applied. The system is assumed to be in a state of idle (operating at a lower temperature, but not off) in anticipation of snowfall during portions of the winter season.

To determine the requirements for heating and cooling of buildings, "Chapter 3.5: System Performance Requirements", in the Final Report Solar Heating and Cooling of Buildings [61] presents an excellent analysis of building energy requirements in different climate conditions. As with the snow melting system analysis, several key climatic parameters (average annual number of degree days below 65 F, above 65 F; annual distribution of wet bulb temperatures; enthalpy of the air) were applied to a set of building design parameters (area, wall type, ventilation, and occupancy) to estimate annual requirements for both heating and cooling of buildings. Table E-19 displays some results of this analysis for 12 of the 14 cities [61]. The store (15,000 ft.^{2} single-story open area) and office (10,000 ft.^{2} two-story divided area) building types are chosen as the best representatives of the unit energy requirements for AGT Garages and Buildings, respectively.

Figure E-5 shows 3 summer climates and 3 winter climates developed in Reference 61 and the approximate location of the 12 representative cities used for the SOS data base. This figure should aid an analyst in determining which city best models the climates of other cities not listed. The classifications are based solely on degree days.

Other major uses of energy are the operation of the wayside communications and control equipment and the general electrical energy used in buildings and garages (lighting, equipment operation, etc.). Computed from annual energy consumptions for the buildings and garages designed in the GM Dual Mode Study [39], the values for general electrical consumption of buildings and garages, respectively, are:

EBLDE = 67 KWH/m^2 per year

EGARE = 343 KWH/m^2 per year

TABLE E-19. HEATING AND COOLING ENERGY

City	Function	Annual Energy - BTU/m^2	
		Office (AGT bldg.)	Store (AGT gar.).
Miami	Cooling	950,356	2,054,744
	Heating	0	0
Los Angeles	Cooling	154,522	522,433
	Heating	20,322	0
Albequerque	Cooling	280,611	653,100
	Heating	99,933	0
Denver/ Colo. Springs	Cooling	187,467	449,167
	Heating	162,044	5,178
Dallas/Ft. Worth	Cooling	511,078	1,150,422
	Heating	33,411	0
Memphis/ Nashville	Cooling	404,900	880,289
	Heating	70,944	0
Washington D.C.	Cooling	307,467	699,244
	Heating	87,633	0
Salt Lake/Odgen	Cooling	225,378	507,467
	Heating	153,922	4,322
Seattle	Cooling	70,500	227,933
	Heating	97,456	0
Boston	Cooling	152,356	408,889
	Heating	127,989	2,133
Chicago	Cooling	213,333	500,000
	Heating	150,678	5,278
New York	Cooling	243,444	573,922
	Heating	103,722	100

Winter Heating Seasons

Summer Cooling Seasons

FIGURE E-5. REGIONS OF SIMILAR CLIMATIC CONDITIONS

The energy consumed in the operation of the communications and control equipment reported in that study and assumed in the System Operations Studies is:

EWCC = 9895 KWH/lane km per year

E.8 ENERGY AND POLLUTION CONVERSIONS

After all energy requirements are determined (in BTU's), these values must be converted into:

- Appropriate requirements by source type
- Equivalent common measure
- Dollar costs
- Equivalent amounts of pollution

The first two types of calculations are straight scientific conversions; the third calculation requires a knowledge of market conditions; and the last conversion requires a broad analysis with several assumptions.

To report the energy requirements by type implies that the source of energy to perform a given function is known. In the SOS Cost Model, the following function-type associations are assumed:

AGT Vehicle propulsion	- Electricity, Gasoline, or Diesel
Feeder Vehicle propulsion	- Gasoline, or Diesel
Building, Garage, Guideway Heating	- Natural Gas
Building, Garage Cooling	- Electricity
Other General Energy Uses	- Electricity

Vehicle propulsion energy is input as amount of source (kW-h or liters per year), while heating and cooling requirements are determined by the SCM independent of source (BTU per year). Thus, heating and cooling energy must be converted to a source type by the appropriate factor, including the conversion efficiency:

ECONVC = 1 kW-h per 3,412 BTU (electric cooling) @ 100% eff.

ECONVH = 1 m^3 per 34,133 BTU (natural gas heat) @ 100% eff.

All energy can then be converted to an equivalent measure by another conversion, in this case to kW-h [62]

EKWH (1) = 1.0 kW-h per kW-h electricity

EKWH (2) = 10.0 kW-h per m^3 natural gas

EKWH (3) = 9.6 kW-h per l gasoline

EKWH (4) = 10.7 kW-h per l diesel fuel

Finally, energy can be costed by source:

CENER (1) = $0.0420 per kW-h electricity

CENER (2) = $0.0469 per m^3 natural gas

CENER (3) = $0.1105 per liter gasoline

CENER (4) = $0.0890 per liter diesel fuel

The first two costs are escalations of the values assumed in reference [39], and the last two are based on estimated values of $.36 and $.29 per gallon before taxes.

In considering the amounts of pollution produced in the consumption of each energy source, five atmospheric pollutants are considered:

- Hydrocarbons
- Carbon Monoxide
- Sulfur Dioxide
- Nitrous Oxides
- Particulates

In computing the pollution associated with natural gas, gasoline, and diesel fuel, direct emissions have been calculated for general combustion conditions [62,63]. Since electricity is a secondary source of energy, the pollution associated with it is indirect (i.e. -- at the production end), and several assumptions are necessary. From 1970 data produced by the Federal Power Commission [65], national averages for the amounts of primary energy sources consumed in the production of electricity were used to weight the amount of pollutants produced in generating electricity. Thus, Table E-20 shows the estimated pollution associated with each energy source. The natural gas figures are from reference 63; the hydrocarbons, carbon monoxide, and sulfur dioxide figures for gasoline and diesel internal combustion engines (buses and trucks at 3.5 mpg) are from reference 64; and the nitrous oxide and particulate data for gasoline and diesel internal combustion engines (unregulated auto emissions) are from reference 63.

TABLE E-20. POLLUTION CONVERSIONS

	HC_x	CO	SO_2	N_xO	Partic.
Electricity gm/kW-h	0	0	12.8155	3.7957	3.1085
Natural Gas gm/m^3	0.128	0.320	0.0096	1.920	0.302
Gasoline gm/l	20.7	198.9	15.4	24.0	1.4
Diesel gm/l	0.5	20.0	4.7	46.8	13.0

E.9 AMORTIZATION FACTORS

The information used to amortize all capital costs are the life spans of the various structures and equipment, the proportion of cost returned at normal salvage (end of life span), and the interest rate.

In surveying the data reported in Reference 5 regarding component life spans, no structured pattern was evident. Manufacturers' estimates of the useful life expectancies for structures and equipment often vary between 10 and 40 years in 5 year intervals, with the higher values for structures and the lower values for equipment. Since most unit cost estimates are independent of manufacturer (and often system type), it is unnecessary to differentiate specific systems by their predicted life spans, except in the case of vehicles, for which manufacturers' estimates are considered. Thus, using the following UMTA guidelines for equipment life spans [66]:

Bus Vehicles	12 years
Rail Vehicles	25-30 years
Other Fixed Assets	40 years

and the observation that most manufacturers quote lower life spans for electronic equipment than for structures, the estimates in Table E-21 are derived for all investments other than AGT vehicles, which will in some way be system dependent.

The life spans for AGT vehicles are estimated by inspecting manufacturers' quotes in Table E-22. To best model reality, values of deployed systems are considered dominant within any one class of vehicles. If one assumes that the cost effect of a longer life span can be reasonably normalized out for comparative purposes, a crude rule of thumb would predict a monotonic -- increasing cost per year with vehicle size. This check breaks down within GRT, where an abrupt jump in life spans arises:

Class	Life	Cost/Year
PRT	10	3,700 - 5,700
DMT	12	3,800 - 14,000
SGRT	10	16,700
IGRT	20	11,900
LGRT	20	22,250
ART	20	40,000

In attempting to gain more consistency among all classes, the GRT systems are aggregated to all have the same vehicle life spans:

Class	Life	Cost/Year
PRT	10	3,700 - 5,700
DMT	12	3,800 - 14,000
GRT	15	11,100 (small)
	15	15,800 (intermediate)
	15	29,700 (large)
ART	20	40,000

This life span assignment presents a smoother flow between classes, and is consistent (by the rule of thumb) with cost estimates to be used.

In estimating the normal end of life salvage values, zero is used for all items in the SOS study. Thus, no value is received for items at their expiration, although premature salvages are calculated using straight-line depreciation by the model. In estimating interest rates to be used, three values are suggested by UMTA:[66] 4%, 7%, and 10%. The third value, 10%,

TABLE E-21. STRUCTURES AND EQUIPMENT LIFE SPANS

Type of Investment	Mnemonics	Life
Structures	LCNBLD	40
	LFGAR	40
	LGD	40
	LMTGAR	40
	LMTSER	40
	LSTBLD	40
Mechanical Equipment	LFEQ	40
	LMTEQ	40
	LSNW	40
	LSPARE	40
Electronic Equipment	LSTEQ	25
	LWCC	25
	LCEQ	25
	LPMEQ	25
Power Distribution	LPOW	20
Feeder Vehicles	LFVEH	12

TABLE E-22. VEHICLE LIFE SPANS

System	Class	Life Span	Representative Life by Class	Representative Life Grouping GRT
Aerial Transit Cabinentaxi* Aerospace CVS	PRT-l PRT-l PRT-h PRT-h	15 10 10 5	10	10
GM Dual Mode TTI Dual Mode UMTA Bus*	DMT DMT-p —	10 20 12	12	12
Ford * H-Bahn Morgantown* GEC/Minitram	SGRT-l SGRT-l SGRT-l SGRT-h	10 20-25 10 20	10	15
Airtrans* Rohr P Unimobil II KVC Mini/Mono Project 21 Unimobile VONA	IGRT-l IGRT-l IGRT-l IGRT-h IGRT-h IGRT-h IGRT-h IGRT-h	20 15 10 10 10 15 15 13	20	15
——	LGRT	—	20	15
BART *	ART	20	20	20

* denotes a system assumed to be dominant for the class

was used in the SOS analyses for computing both amortized capital costs and net present values.

E.10 INFLATION AND MODIFICATION FACTORS

The cost factors used to model system cost include the indices used to correct past prices to a base year value, the inflation factors used to model price changes throughout the life cycle period, factors to differentiate between certain construction conditions, and factors to account for spare parts inventory and administrative and general costs.

The base year correction of past prices is performed by applying a ratio of a relative index of the base year value to a previous year index. Four categories of capital cost types, Vehicles, Construction, Electronics, and General; and three categories of variable cost types, Operations, Maintenance, and Energy; seem adequate to model the major effects of the economy on AGT expenditures. Table E-23 lists the indices and references. All values for 1977 and some values for 1976 are extrapolations of the documented data, derived from the average increase over all previous years. The indices include the effects of both price (relative to each other) and dollar (monetary value) inflations. The index values listed in Table E-23 are used by the analyst to adjust all unit cost inputs to a common base year.

To inflate the costs incurred at different times throughout the life cycle period, a factor is applied to account for price changes with the effects of general inflation normalized out. This modeling approach is labeled constant dollar-current price costing, since, while prices may change relative to one another, all values are reported in constant base year dollars. Thus, from Table E-23, all values are normalized (divided by) the general index and then used to calculate the average annual increase factor:

Category	Annual Inflator (INF)
Electronics	0.974
Construction	1.023
Vehicles	1.022
Energy	1.048

TABLE E-23. PAST PRICE INDICES

Category	Documented INDEX Values										Sources	Extrapolated	
	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976		1976	1977
Electronics	100.0	101.3	102.9	106.2	109.5	110.4	112.4	125.0	140.7	—	Wholesale Price Index 67	147.0	153.5
Construction	100.0	107.9	118.6	129.5	147.8	163.8	177.1	188.8	206.7	—	Wholesale Price Index 67	226.4	247.9
Vehicles	—	—	—	115.1	121.1	128.7	134.7	163.8	201.2	214.0	W.P.I. for RR Equip. 67	—	237.9
Energy	100.0	98.9	100.9	106.2	114.2	118.6	134.3	208.3	245.1	—	W.P.I. for Electricity 67	276.8	312.7
Operations	—	—	—	125.2	135.8	144.9	155.4	173.3	192.9	210.3	Transit Union Rates 67	—	229.3
Maintenance	—	—	—	121.3	130.2	138.2	147.3	165.5	192.2	208.5	Weighted average parts/labor 68	—	228.3
General	100.0	102.5	106.5	110.4	113.9	119.1	134.7	160.1	174.9	—	General Wholesale Price Index 67	187.8	201.6

Operations	0.995
Maintenance	1.001
General	1.000

It is suggested by UMTA [66] that any such values be applied to no more than 15 years, after which the uncertainty of long-term inflation makes any further modeling undesirable. The SCM applies the annual inflator values when calculating expenses incurred after the base year throughout the life cycle period.

The other cost factors used by the System Cost Model modify values to account for certain conditions. These cost modification factors are listed in Table E-24 along with the default values and the rationale and references for each.

TABLE E-24. COST MODIFICATION FACTORS

Mnemonics	Description	Rationale	Value	Reference
XFVEH XDSP XCNTRL XSNW XSTEQ	Various spare parts inventory costs, as proportions of respective initial costs	Must stock spare parts for major equipment.	0.03	39
XADM XFADM	Cost for administrative services, as proportion of other O & M costs	Includes all general, supervisory and insurance costs	0.08	39
XURBC	Relative cost to construct within urbanized area	Increased disruption will affect construction costs	1.25	69
XDUALC	Relative cost per lane for dual vs. single lane quideway construction	A 1/3 savings for dual lane over 2 single lanes (16% per lane)	0.84	39
XDUALP	Relative cost per lane for dual vs. single lane power installation	No savings. Must duplicate most components	1.0	—

APPENDIX F

AVAILABILITY ANALYSIS

To perform an availability analysis of any system using the System Availability Model (SAM) requires an understanding of the reliability characteristics of the system hardware, the consequences of failures on system operation, and the failure management techniques applicable to the system. The purpose of this appendix is to present a procedure for gaining this understanding and for applying it to the evaluation of system availability using the SOS software.

F.1 HARDWARE RELIABILITY PREDICTION

The process of estimating subsystem failure rates for input to the SAM begins with a detailed description of the system under investigation. The failure modes of each component and the effects on system operation of each failure mode are determined. The failure rate associated with each mode of failure is estimated. Finally, the failure rate data are aggregated to the subsystem level.

The generation of a hardware description of the system being analyzed is a necessary first step in estimating hardware reliability characteristics to be used in an availability analysis. The hardware description should include as much detail about the system as possible; i.e., the description should be at the lowest level consistent with the analyst's knowledge of the system design, the purpose of the analysis, and the resources available for the study. The first section of Appendix G is a description of a conceptual GRT system which was analyzed during the System Operations Studies. A description of this nature is used to develop a more detailed hardware breakdown. Table F-1 illustrates increasing levels of hardware detail that may be considered in the determination of subsystem reliability. All subsystems need not be defined to the same level of detail. The second section of Appendix G illustrates a hardware breakdown for the GRT system described in the first section of the appendix. To assure consistency with SAM input requirements, the system has been partitioned into four major

TABLE F-1. HARDWARE DESCRIPTION

INCREASING LEVEL OF DETAIL →

VEHICLE	VEHICLE	VEHICLE
STATION	PROPULSION	PROPULSION
GUIDEWAY	BODY AND CHASSIS	BEARING
CENTRAL	LATERAL CONTROL	COMMUTATOR
	BRAKES	BRUSHES
	CONTROL ELECTRONICS	ARMATURE
	COMMUNICATIONS	ARMATURE CONTROL
		GEAR
	STATION	FIELD WINDING
	DOORS	FIELD SUPPLY
	DOCKING MECHANISM	BODY AND CHASSIS
	CONTROLLER	SPRING
	TICKETING	SHOCK ABSORBER
		WHEEL BEARING
		TIRE
		DOOR ACTUATOR
		DOOR ACTUATOR MOTOR

subsystems: guideway, vehicle, stations, and central control. Each subsystem is defined in terms of components and, in some cases, piece parts. An estimate of the number of components required per subassembly is also given in the table.

Using the system description and hardware breakdown, an understanding of the impact of individual failures on system operation must be established. Of particular interest here is to determine how and to what extent all identifiable failure occurrences affect the system. This requires that some level of failure modes and effects analysis (FMEA) be performed in which modes of failure are postulated, and the consequences of failure are established. As an example, Section G.3 of Appendix G identifies failure modes for the components and piece parts listed in the hardware breakdown (Section G.2). Based on this listing of failure modes, the effects of each failure on the various subsystems are determined. For the purpose of evaluating system availability, consideration of failure effects can be limited to two major categories: vehicle stoppage and vehicle degradation. These two failure effects produce immediate and potentially severe consequences in terms of vehicle downtime and passenger delay. When a vehicle stops on the guideway, not only are the passengers on board the stopped vehicle delayed, but upstream vehicles which cannot be rerouted around the blockage are also delayed. Similarly, a vehicle which is prevented from operating at normal system velocity delays passengers on board the degraded vehicle and may cause upstream vehicles to queue.

After failure modes and top level effects have been identified, piece part failure rates are then established based on available resource data. For mature AGT systems, actual demonstrated reliability data may be available. Otherwise resource data may include any one or a combination of data from sources such as empirical information, Military Handbook 217C, Rome Air Development Center - Technical Report, Government Industry Data Exchange Program, Advanced Subsystem Development Program, or engineering estimates. Section G.4 in Appendix G lists estimated failure rate data in units of failures per 10^6 hours for the GRT system described in the appendix.

The next step is to determine the proportion of the failure occurrences for each component which result in each of the two major failure effects. Since not all failures result in a vehicle stoppage or degradation, the proportion of component failures which do not affect system operation from an availability point of view should also be established. Finally, the component and piece part failure rates are aggregated to the subsystem level for input to the System Availability Model (SAM). The allocation of failure rates between major failure effects and the aggregation of data to the subsystem level are illustrated in Section G.5 of Appendix G for a GRT system.

F.2 FAILURE MANAGEMENT STRATEGY EVALUATION

System availability is a measure of the extent to which vehicles and passengers are delayed by failures relative to normal, failure-free operation. The SAM, however, does not in itself determine how vehicles and passengers are affected by failure events. The model combines the consequences of failures (which are determined outside the model) with the likelihood of the event occurring (failure rate data within the model) to generate aggregate vehicle and passenger delay parameters used in the availability calculations. The consequences of individual failures in terms of vehicle and passenger delay are required inputs to the SAM, and they can be estimated through simulation using the DESM, through analytical means, or through evaluation of empirical information.

For systems where operational data are available, such as Airtrans[70] and Morgantown[71], the times required to restore the system to operation after a failure may be documented. However when the DESM or analytical means are used to estimate the effects of abnormal system operation, the duration of the failure events must be estimated. The time required to restore service after a failure is primarily a function of the failure management strategies employed by the system. These strategies involve the detection of failures, the removal and/or replacement of a failed vehicle, and the restoration of normal service. The DESM can be used to simulate the operation of the system during a failure and subsequent recovery assuming a variety of failure management strategies. Based on the simulation results,

failure management strategies for specific types of failures are selected for use in estimating the consequences of failures. The strategies for removing a failed vehicle from the guideway which are modeled by the DESM include automatic or manual restart, pushing by another revenue service vehicle, and towing by a service vehicle. Cross-overs and turnbacks can be specified in the network description to speed access by a service vehicle or to help minimize the time required to remove a failed vehicle. Alternative responses of other vehicles whose routes cross the failure location include:

Continue in revenue service using an alternate path to bypass the failure location if possible until forced to queue behind the failure.

Continue traveling on the route deboarding but not boarding passengers until failure recovery is initiated or until forced to queue behind the failure.

Travel to the next station, deboard all passengers, and then continue without stopping at additional stations until forced to queue behind the failed vehicle or until recovery is initiated.

Travel to the next station and wait until failure recovery is initiated.

Passengers who are deboarded before completing their trip enter the boarding queue as failure induced transfers. After the failed vehicle has been removed from service and a replacement vehicle has been dispatched, several alternative vehicle dispatch algorithms can be evaluated for their ability to debunch the vehicles on each route and to quickly restore service.

F.3 FAILURE CONSEQUENCE EVALUATION

If the system being analyzed is quite simple, such as a shuttle or single loop network with a limited number of stations, analytical techniques can be used to establish the consequences of failures. For more complex systems, however, it is necessary to simulate system operation using the DESM to determine failure consequences. Both vehicle downtime and passenger

delay resulting from failures are required inputs to the calculation of system availability. Since a certain amount of vehicle and passenger delay results from normal congestion and demand fluctuations, the consequences of specific failures must be estimated by comparing system performance data generated by the DESM in a failure-free environment (reference run) with that generated during and immediately after failures have been introduced into the simulation (failure runs). The vehicle downtime estimated for each simulated failure condition is calculated using the following formula:

$$\frac{\text{Vehicle Distance Traveled (Reference)} - \text{Vehicle Distance Traveled (Failure)}}{\text{Average Vehicle Velocity (Reference)}}$$

Passenger delay data are determined by the SAM by comparing trip logs generated by the DESM for each failure condition with a reference trip log. A trip log is a list generated by the DESM which records trip time data for each trip completed during the simulation.

To properly determine the extent of the delay resulting from a particular failure event, the simulation periods for both the reference and failure runs of the DESM must extend sufficiently beyond the failure event such that normal system operation is approached before the end of the simulation. Indications of normal system operation are comparable values of station platform queues and excess travel time for the reference run and the failure run. An additional indication that normal scheduled service has been restored is approximate equality of the minimum and maximum interdispatch times for each individual route. This condition indicates that approximately equal spacing of vehicles on each route has been restored. The simulation period of the failure run often must be longer than that of the reference run to minimize the number of unmatched trips. Unmatched trips are trips that occur in the trip log of the reference run of the DESM that are not completed during the simulation period of the failure run and, therefore, do not appear in the trip log of the failure run. The number of unmatched trips is an output of the SAM.

In conducting an availability analysis, the analyst must select a manageable number of failures and failure responses to represent the

consequences of all possible failures. It is suggested that these representative consequences be defined by first partitioning the system deployment and then simulating representative failure conditions within each category. The partitioning of AGT systems into subsystems for the purpose of estimating failure rates has already been discussed. The grouping of failures into two categories -- those that cause a vehicle to stop and those that cause a vehicle to travel at reduced speed, has also been discussed. The manner in which failures of each subsystem are modeled in the DESM are described below. In addition, the influences of demand and failure location on the consequences of failures are discussed.

A vehicle failure can be specified to occur on any guideway link and at any specific time during the simulation. Two types of vehicle failure, stoppage and degradation, can be specified. In both cases the failed vehicle remains immobilized until recovery is initiated, proceeds to the next station at reduced speed to deboard all passengers, and then proceeds to the nearest maintenance facility at reduced speed and disappears from the active fleet. The initial delay time prior to the initiation of recovery is determined during the failure management analysis; it may be zero if the vehicle is merely degraded with respect to operating velocity.

A guideway link failure which results in a vehicle stoppage can be introduced in the same way that a vehicle failure is specified. However, upon recovery of a guideway link failure, vehicles are not taken out of service but are merely restarted. A guideway link failure which results in vehicles not being able to operate at nominal velocity on a set of links for an extended period of time can be modeled by reducing the specified value of velocity on selected links before running the simulation.

Two types of station failures can be specified to occur at any time during a simulation. A station link can be failed by not permitting vehicles to exit the link and/or not allowing vehicles to enter the link. An entire station can also be failed by not permitting vehicles to enter the input ramp or to exit the output ramp. After a suitable delay, the failed links are recovered and vehicles that have been stopped by the failure are restarted. Station link degradation failures can be modeled by temporarily increasing the travel time on selected station links.

Two major effects of central management failures can be modeled. A complete system shutdown can be simulated by simultaneously failing all guideway links. This creates the effect of stopping all vehicle movement at the time the failure is introduced. System recovery and restart can be initiated on all links simultaneously or sequentially on different segments of the network. Degraded system operation can be represented by simulating system operation with reduced values of velocity on all guideway links.

The consequences of these failure conditions in terms of vehicle downtime and passenger delay depend not only on the duration of the event itself but also on the passenger demand, the number of vehicles operating in the system at the time of the failure, and the network location of the failure. Therefore, daily demand and supply variations and network geometry represent two more important dimensions of the availability issue. The projected demand for an AGT system nearly always exhibits a cyclic or repetitive characteristic over a period of time. System capacity and operating characteristics are usually specified based on two or more demand distributions representing peak and off-peak demand. Consequences of each type of subsystem failure should generally be evaluated separately for each significantly different demand distribution.

Since the network geometry of systems is generally not symmetric, the interaction of vehicles may be influenced differently by the same failure event occurring at different network locations. Various areas of a network may also have different quantities of operational hardware whose failures will affect system operation. Different areas, for example, can have different numbers of control blocks, stations, wayside control elements, etc. Therefore, except for very simple systems such as shuttles, line hauls, and single loops, network partitioning should be considered in the analysis. If analysis shows that there is a passenger or vehicle delay sensitivity to the location of failures, the network should be partitioned into regions within which the consequences of failure events are similar. The partitioned network characteristics must also be input to the SAM. This enables the SAM to predict the number of failures which are expected to occur in each region based on vehicle operating time in the region, quantity of equipment or stations in the region, etc. It may also be necessary to

partition the network into regions based on the time required to clear failures or failed vehicles from the network. In the availability analysis, the consequences of representative failures in each region of the network are evaluated.

Analyst judgment must be used to partition the deployment for availability analysis and to select the representative failure events. The scope of the availability analysis task is determined to a large extent by deployment partitioning. The number of subsystems, the number of failure categories (stoppage, degradation, etc.), the number of demand periods, and the number of network regions all have a multiplicative effect on the total number of DESM simulations required to characterize failure consequences.

F.4 SYSTEM AVAILABILITY EVALUATION

Once the system deployment has been partitioned into appropriate subsystems, network regions, and demand periods, failure rate data has been generated, and representative failure consequences have been established, the SAM can be used to calculate system availability parameters. In addition to measures of system availability, the SAM also estimates the spare vehicle requirements of a system. The estimate (based on Markov queueing theory) requires, in addition to the availability calculation inputs, the operating fleet size, scheduled vehicle maintenance frequency and times, and unscheduled maintenance time.

Here, as when evaluating availability, the model can be used to parametrically evaluate the spare vehicle requirements where vehicle reliability, scheduled maintenance frequency, scheduled maintenance time, and unscheduled maintenance time can be variables in the analysis.

The SAM contains a readily accessible summary of the input parameters used in the availability analysis. This summary includes, in addition to the input data values, a listing of the failure conditions used in the analysis and an uncompleted trip log record (unmatched trips). Unmatched trips are trips that occur in the trip record of a reference run of the DESM

that are not completed during the simulation period when a failure condition is simulated. If the simulation period of the failed condition is of sufficient length, no unmatched trips will occur. The model output summary also contains the failure rate causal factor parameters, a summary of the failure mode partitioning for the subsystem failure rates, and the demand, region, and causal factor partitioning applicable to the analysis.

The model provides the analyst with the opportunity to select a range of passenger delay thresholds or increments of delay time which are pertinent to the analysis. The passenger delay data, i.e., number of passenger trips delayed for a time greater than each threshold value, is provided as an output of the model. The computation of the passenger availability measure is provided for each threshold value used in the analysis.

The output of the SAM contains a summary of the vehicle delay time for each network region and demand period as well as the calculated vehicle availability measure.

The SAM provides a three dimensional summary of the probability of having spare vehicles available for service when required as a function of the number of spare vehicles and the level of maintenance servicing capacity (number of servicing bays). The summary is representative of the fixed set of system reliability and maintenance characteristics being used in the analysis. This provides the analyst with the opportunity to predict system requirements and perform system cost trade-offs between maintenance facility capacity and spare vehicles.

In an analysis of alternative AGT deployments, system availability is often evaluated as a comparative measure of system performance. However, the DESM and SAM can also be used to support a parametric trade-off analysis in which availability parameters such as subsystem reliability, mean time to restore service, and failure management strategies are traded off. For example, the effects on system availability of variations in subsystem failure rates can be evaluated through repeated use of the SAM using constant failure consequence input. If subsystem reliability is given, the maximum allowable time to recover from failures can be determined by

establishing the impact on system availability of a range of downtime durations. As an example, the effect of a range of average failure durations (such as 5, 10, and 15 minutes) can be established through simulation with the DESM. For each failure duration, the SAM can be used to determine the level of system availability which can be achieved. In a similar manner the effects on availability of system design characteristics, such as fleet size and network configuration, can be established.

APPENDIX G

EXAMPLE RESULTS OF A GRT SYSTEM RELIABILITY ANALYSIS

In this appendix the intermediate and final results of a reliability analysis conducted on a conceptual GRT system during the System Operations Studies are presented to help illustrate the procedure described in Appendix F. The system is first described in functional terms. The functional description is followed by a more detailed hardware breakdown which defines each major subsystem in terms of components and piece parts. Possible failure modes are postulated for each entry in the hardware breakdown, and failure rates are estimated. Finally component failure rates are aggregated to the subsystem level and subsystem failure rates are allocated between the two assumed failure types -- stoppage and degradation.

G.1 SYSTEM DESCRIPTION

This system is a high speed SGRT operating in a high demand metropolitan environment. The system is operated in a demand responsive service mode. The system is deployed on a fully connected grid network and serves 40 off-line stations. The system is described in the following paragraphs in terms of four major subsystems: guideway, vehicle, station, and central management.

GUIDEWAY

Structure. The guideway structure is elevated and is constructed of 25 meter sections of prestressed concrete. The guideway is a fully connected grid network containing 112 lane km of dual lane and 39 km of single lane guideway. The guideway provides power, weather protection, lateral control, and communication as integral features of its construction.

Power. 500 volt, 3 phase, 50 Hz power is supplied by 20 substations located at intervals along the guideway route. Provision for interconnections eliminate the possibility of shutting the guideway down in case one

substation fails. Nominal maximum demand of 700 Kw per substation can be applied to three power rails installed on the guideway sidewall.

Weather Protection. The power rails are shielded from inclement weather by an insulating cover. Drainage for the guideway consists of a gutter down the center of the guideway with drains at intervals which connect with a duct embedded in the structure. The duct is provided with laterals to the municipal storm drainage system. Snow and ice accumulation on the guideway is prevented by additional ducts embedded in the guideway through which heated fluid can be circulated.

Wayside Communication. The entire guideway length is divided into blocks. Each block has a loop embedded in the surface which serves both as a vehicle sensor and transmitting/receiving antenna. Each block also has an individual transmitting/receiving unit which communicates with the vehicle, other blocks, and central management. Separate sensing coils are located at station approaches to pick up incoming vehicles and transmit the stop command for precision vehicle docking.

VEHICLE

The vehicle is 5 m long, has a mass of 3597 Kg, and is powered by a single 200 Kw dc motor. Vehicle capacity is 15, and seating is provided for 8 passengers. The active fleet includes 556 vehicles.

Body and Chassis. The vehicle body structure is lightweight all-aluminum with a single biparting door on one side. A climate control system is provided to maintain the internal temperature within the range of 18° to $27^{\circ}C$. Internal lights are recessed and the seating is of rigid molded plastic. A closed circuit TV camera is provided at one end of the car. The suspension consists of a pivoted truck at each end with foam filled rubber tires. Automotive type springs and shock absorbers are used, and the propulsion motor drives through an automotive type differential.

Lateral Control. Vehicle position within the guideway is controlled by a soft lateral control system which employs a pair of magnetic pickups under

the car which sense the magnetic field around a wire embedded in the guideway. Both trucks steer so as to provide a minimum turning radius of 10 M. The lateral control system sensors establish the vehicle position within the guideway and provide closed loop control. Switching capability is provided for by energizing a selected control wire at merge/diverge junctions under central management control. The vehicle control logic is mechanized to stop the vehicle if one and only one wire is not energized.

Brakes. The brake system consists of dynamic electrical braking with a friction brake backup on the motor shaft. For fail-safe operation, the deenergized friction brake mode is with brakes applied. An override is provided to manually release the brakes.

Propulsion. Motive power is provided by a 450 vdc shunt traction motor rated at 200 Kw. Power supplied at 500 V, 3 phase, 60 Hz is modulated by a phase controlled rectifier to provide controlled torque output and soft starting. A separate field supply rectifier controls the field current magnitude to provide dynamic braking and constant horsepower output above base speed. The motor drives into an automotive type differential.

Control Electronics. Longitudinal control of the vehicle is effected by velocity, acceleration and deceleration commands received from the wayside communication system. In addition, a "stop" command is provided for fail-safe operation, and an "inch" command is provided for precision docking control. Headway control is normally exercised by the central management computer. However, an on-board headway control is implemented through the wayside communication system to maintain safe system headways. In operation, the central management computer is informed of the vehicle position through the wayside communication system. Sensors for "no motion" and "doorway obstruction" interface with the control electronics. The controller utilizes commercially available integrated circuit components and is powered from an onboard battery/charger combination.

Communications. Command communications are implemented through the inductive loops embedded in the guideway. The vehicle transmits its identification code, velocity, and operational status to the wayside

communication system. It receives the position and velocity of the vehicles immediately ahead and behind, velocity and auxiliary commands for station docking, door operation, and station departure. A closed circuit TV camera on board the vehicle is coupled to a "leaky" coaxial cable installed at trackside. This also is used to provide audio communication with the vehicle.

STATION

Stations contain currency changers, ticketing, and passenger handling facilities. A waiting area is provided for paid passengers. The station conceptual design is one wherein the failure of a single change or ticketing machine or a turnstile does not result in passengers incurring delays at the station.

Doors. The waiting area is fully enclosed with biparting doors to prevent the passengers from gaining access to the guideway. The doors are controlled by the station controller so that they open only when a vehicle is properly positioned and at a full stop. A turnstile is positioned ahead of the door to accept the passenger's ticket and transmit destination data and "passenger served" signal to the station controller.

Docking Mechanism. A sensing coil embedded in the guideway at the approach to the station signals the approach of a vehicle. Sensing coils at the docking position are used for final docking control.

Controller. A microprocessor is used as the station controller to provide docking and door control. The station controller communicates with the central management computer by means of hard-wired communication lines for system control.

CENTRAL MANAGEMENT

The central management function controls overall system operation by generating vehicle routes, scheduling vehicle stops, calling up additional vehicles, and dispatching excess vehicles to storage areas.

Computer. A digital computer is used for central management, communication with vehicles, and station controllers.

Communication. Data communication with the vehicles is provided by means of the wayside communication system. The central management communication unit acts as a signal conditioner and interface between the computer, wayside communication system, and station controller. Audio and video communication with the vehicles is also provided. The surveillance link is activated by a control signal sent to the vehicle. Picking up a handset in the vehicle establishes audio communication with the operator. A communication line is also open to the maintenance and storage facility.

G.2 HARDWARE BREAKDOWN

Table G-1 lists hardware components and, in some cases, piece parts which comprise each of the four major subsystems of the subject GRT system. The "indenture" indicates the relative level of detail represented by each component and is used later to help aggregate the reliability data to the subsystem level. A much more detailed hardware breakdown would probably be used in the analysis of an existing system because more detailed reliability data would likely be available. However, since the purpose of the hardware breakdown is to provide a framework for reliability estimates, the availability of failure rate data or estimates should dictate the level of system definition in this analysis.

G.3 SUBSYSTEM FAILURE MODES

Table G-2 lists postulated failure modes for the components which comprise the subject GRT system.

TABLE G-1 (1 of 4). SUBSYSTEM HARDWARE BREAKDOWN

ITEM	INDENTURE	QUANTITY
GUIDEWAY	1	1
Structure	2	1
Roadway	2	1
Power Rail	2	120
Guide Wire	2	54
Substation	2	20
Weather Protection	2	20
Wayside Communication	2	1
Coaxial Cable	3	1
Inductive Loop	3	5254
Transmitter/Receiver	3	5254
VEHICLE	1	556
Body and Chassis	2	1
Truck	3	2
Spring	4	2
Shock Absorber	4	2
Wheel	4	2
Axle	4	1
Tire	4	2
Door	3	1
Actuator	4	1
Drive Motor	4	1
Interlock	4	1
Environment Control	3	1
Air Conditioning	4	1
Heater	4	1
Ventilating	4	1
Security	3	1
TV Camera	4	1

TABLE G-1 (2 of 4). SUBSYSTEM HARDWARE BREAKDOWN

Lateral Control	2	1
Magnetic Pickup	3	2
Actuator	3	2
Brakes	2	1
Brake Grid	3	1
Friction	3	1
Propulsion	2	1
Motor	3	1
Gear Unit	3	1
Controller	3	1
Phase Delay Rectifier	4	1
SCR	5	6
Resistor (W-W)	5	30
Capacitor (P-P)	5	9
Diode	5	60
Transformer	5	6
Transistor	5	6
Field Supply	4	1
SCR	5	6
Resistor (W-W)	5	30
Capacitor (P-P)	5	9
Diode	5	60
Transformer	5	6
Transistor	5	6
Control Electronics	2	1
Motor Control Electronics	3	1
IC, Digital	4	41
IC, Linear	4	9
Resistor (CC)	4	171
Capacitor (Cer.)	4	56
Diode	4	35
Transistor	4	9

TABLE G-1 (3 of 4). SUBSYSTEM HARDWARE BREAKDOWN

Vehicle Control Electronics	3	1
IC, Digital	4	40
IC, Linear	4	30
IC, ROM	4	2
IC, RAM	4	4
Resistor (CC)	4	105
Capacitor (Cer.)	4	48
Diode	4	35
Transistor	4	4
Communications	2	1
Transmitter/Receiver	3	1
STATION	1	40
Doors	2	3
Actuator	3	1
Drive Motor	3	1
Interlock	3	1
Docking Mechanism	2	3
Sensing Coil	3	1
Vehicle Storage Bay	2	1
Sensing Coil	3	6
Controller	2	1
IC, Digital	3	30
IC, Linear	3	22
IC, ROM	3	2
IC, RAM	3	4
Resistor (CC)	3	95
Capacitor (Cer.)	3	43
Diode	3	31
Transistor	3	1

TABLE G-1 (4 of 4). SUBSYSTEM HARDWARE BREAKDOWN

CENTRAL MANAGEMENT	1	1
Computer	2	1
IC, Digital	3	30
IC, Linear	3	22
IC, ROM	3	16
IC, RAM	3	24
Resistor (CC)	3	95
Capacitor (Cer.)	3	43
Diode	3	31
Transistor	3	28
Communications	2	1
TV Monitor	3	4
Transmitter/Receiver	3	1

TABLE G-2 (1 of 3). POSTULATED FAILURE MODES

SUBSYSTEM	MAJOR COMPONENT	FAILURE MODE
VEHICLE	Body and Chassis	Broken spring Defective shock absorber Defective wheel/axle bearing Tire failure Door actuator failed -closed Door actuator failed -open Motor failed (door closed) Motor failed (door open) Interlock failed (open) Interlock failed (closed) Air conditioning failed Heating failed Ventilating failed Camera failed
	Lateral Control	Actuator inoperative Actuator hardover Actuator out of specification Sensor failed -on Sensor failed -off
	Brakes	Brake grid open Brake solenoid failed Brake spring failed
	Propulsion	Motor bearing failed Commutator/brushes worn Shorted armature Open armature Shorted field Open field Gear unit bearing failed Worn gears Gear unit leaking Broken gear Shorted SCR (arm. cont.) Open SCR (arm. cont.) Shorted SCR (field supply) Open SCR (field supply)
	Control Electronics	SCR gate signal failed -on SCR gate signal failed -off Fault logic failed -on Fault logic failed -off

TABLE G-2 (2 of 3). POSTULATED FAILURE MODES

SUBSYSTEM	MAJOR COMPONENT	FAILURE MODE
		Drive command failed -off Drive command failed -on Brake command failed -off Brake command failed -on Torque command too high Torque command too low Brake command too high Brake command too low Door command failed off Door command failed on Excessive speed command Low speed command "Forward" failed -on "Forward" failed -off "Reverse" failed -on "Reverse" failed -off "Emergency Stop" failed -on "Emergency Stop" failed -off
	Communications	T/R failed
STATION	Controller	Data transmission error Door command failed -off Door command failed -on
	Doors	Actuator failed -closed Actuator failed -open Motor failed -closed Motor failed -open Interlock failed -open Interlock failed -closed
	Docking	Docking coil failed
	Storage Bay	Sensing coil failed
GUIDEWAY	Substation	Component failure
	Weather Protection	Leakage Component failure
	Power Rail	Short circuit Open circuit
	Wayside Communication	Coaxial cable failure Inductive loop failure T/R failure

TABLE G-2 (3 of 3). POSTULATED FAILURE MODES

SUBSYSTEM	MAJOR COMPONENT	FAILURE MODE
CENTRAL MANAGEMENT	Computer	Velocity command failed Excessive velocity command Stop command not sent Direction command failed
	Communications	TV failed T/R failed

G.4 HARDWARE RELIABILITY

The estimated failure rate in failures per 10^6 hours for each component is listed in Table G-3. The quantity of each component in each subsystem is also listed. The products of the failure rate and the number of units for the components are summed to get an aggregate failure rate for each subsystem.

G.5 FAILURE RATE DISTRIBUTION BY MODE

In this example two major effects of failures are considered: vehicle stoppage and degraded or reduced velocity operation. The final step in the determination of subsystem reliability is to distribute the failure rate for each subsystem between the two major effects. The failure modes listed in Table G-2 are analyzed to determine which ones result in vehicle stoppages and which ones result in degraded operation. Then the component failure rate data listed in Table G-3 is used to evaluate the proportion of the subsystem failure rate which should be allocated to each major failure effect or mode of system failure. The results of this allocation procedure are presented in Table G-4. The subsystem failure rate for each failure mode is input directly to the SAM to evaluate system availability.

TABLE G-3 (1 of 3). HARDWARE RELIABILITY

ITEM	N	FAILURE SOURCE	λ	Nλ
GUIDEWAY	1		625988.0	
Structure	1		0	0
Roadway	2		0	0
Power Rail	120	RADC-TR-69-458	0.3	36.0
Substation	20	Est	2.0	40.0
Weather Protection	20	RADC-TR-69-458	23.0	460.0
Wayside Communication	1		264785.0	625452.0
Coaxial Cable	1	Est	10.0	10.0
Inductive Loop	5254	Est	8.0	42032.0
Transmitter/Receiver	5254	Est	111.0	583194.0
Guide Wire	54	Est	4.0	216.0
VEHICLE	556		4065.75	
Body and Chassis	1		681.0	681.0
Truck	2	NYCTA	64.4	128.8
Springs	2	Est	2.0	4.0
Shock Absorber	2	Est	2.0	4.0
Wheel	2	Est	5.0	10.0
Axle	1	GIDEP	32.0	32.0
Tire	2	Est	7.2	14.4
Door	1	NYCTA	47.0	47.0
Actuator	1	RADC-TR-69-458	26.0	26.0
Drive Motor	1	217B	9.0	9.0
Interlock	1	Est	12.0	12.0
Environmental Control	1	NYCTA	103.2	103.2
Air Conditioning	1	Est	34.4	34.4
Heaters	1	Est	34.4	34.4
Ventilating	1	Est	34.4	34.4
Security	1		402.0	402.0
TV Camera	1	Est	402.0	402.0
Lateral Control	2		32.7	65.4
Magnetic Pickup	2	Est	4.0	8.0
Actuator	1	Est	24.7	24.7
Brakes	1		64.7	64.7
Electrical	1		2.0	2.0
Brake Grid	1	ASDP	2.0	2.0
Mechanical	1		62.7	62.7
Friction Brake	1	GIDEP	62.7	62.7

TABLE G-3 (2 of 3). HARDWARE RELIABILITY

ITEM	N	FAILURE SOURCE	λ	N λ
Propulsion	1		615.46	615.46
Motor	1	NYCTA	46.0	46.0
Gear Unit	1	GIDEP	24.7	24.7
Controller	1		544.76	544.76
Phase Delay Rectifier	1		269.58	269.58
SCR	6	217B	4.5	27.0
Resistor (W-W)	30	217B	0.28	8.4
Capacitor (P-P)	9	217B	0.03	0.27
Diode	60	217B	3.4	204.0
Transformer	6	217B	0.085	0.51
Transistor	6	217B	4.9	29.4
Field Supply	1		275.18	275.18
SCR	6	217B	4.5	27.0
Resistor (W-W)	30	217B	0.28	8.4
Capacitor (P-P)	9	217B	0.03	0.27
Diode	60	217B	3.4	204.0
Transformer	6	217B	0.085	0.51
Transistor	6	217B	4.9	29.4
Reversing Contractor	1	217B	5.6	5.6
Control Electronics	1		2387.19	2387.19
Motor Control Electronics	1		753.04	753.04
IC, Digital	41	217B	6.83	280.03
IC, Linear	9	217B	25.5	229.5
Resistor (CC)	171	217B	0.11	18.81
Capacitor (Cer)	56	217B	1.1	61.6
Diode	35	217B	3.4	119.0
Transistor	9	217B	4.9	44.1
Vehicle Control Electronics	1		1634.15	1634.15
IC, Digital	40	217B	6.83	273.2
IC, Linear	30	217B	25.5	765.0
IC, ROM	2	217B	105.0	210.0
IC, RAM	4	217B	45.75	183.0
Resistor (CC)	105	217B	0.11	11.55
Capacitor (Cer)	48	217B	1.1	52.8
Diode	35	217B	3.4	119.0
Transistor	4	217B	4.9	19.6
Communications	1		252.0	252.0
Transmitter/Receiver	1	Est	252.0	252.0
STATION	40		784.43	
Doors	3	NYCTA	47.0	141.0
Actuator	1	RADC-TR-69-458	26.0	26.0
Drive Motor	1	217B	9.0	9.0
Interlock	1	Est	12.0	12.0

TABLE G-3 (3 of 3). HARDWARE RELIABILITY

ITEM	N	FAILURE SOURCE	λ	Nλ
Docking Mechanism	3		8.0	24.0
Sensing Coil	1	Est	8.0	8.0
Controller	1		619.43	619.43
IC, Digital	30	217B	2.18	65.4
IC, Linear	22	217B	14.25	313.5
IC, ROM	2	217B	52.5	105.0
IC, RAM	4	217B	22.5	90.0
Resistor (CC)	95	217B	0.025	2.38
Capacitor (Cer)	43	217B	0.55	23.65
Diode	31	217B	0.6	18.6
Transistor	1	217B	0.9	0.9
Central Management	1		1259.43	
Computer	1		1204.43	1204.43
IC, Digital	30	217B	2.18	65.4
IC, Linear	22	217B	14.25	313.5
IC, ROM	8	217B	52.5	420.0
IC, RAM	16	217B	22.5	360.0
Resistor (CC)	95	217B	0.55	2.38
Capacitor (Cer)	43	217B	0.025	23.65
Diode	31	217B	0.6	18.6
Transistor	1	217B	0.9	0.9
Communications	1		55.0	55.0
Transmitter/Receiver	1	Est	55.0	55.0

TABLE G-4. FAILURE RATE DISTRIBUTION BY MODE

	Failure Mode	Component Failure Rate Distribution (%)	Weighted Value Based on Failure Rate	Subsystem Failure Rate Distribution Degraded/Stopped (%)	Subsystem Failure Rate Distribution Degraded/Stopped Failure/10^6 hrs.
VEHICLE					
Body/Chassis	Degraded	59	0.099		
	Stopped	41	0.068		
Lateral Control	Degraded	79	0.013		
	Stopped	21	0.003		
Brakes	Degraded	3	0.001		
	Stopped	97	0.016		
Propulsion	Degraded	49	0.074	45/55	1834/2232
	Stopped	51	0.077		
Control Electronics	Degraded	45	0.264		
	Stopped	55	0.323		
Communications	Degraded	0	0.0		
	Stopped	100	0.062		
STATION					
Controller	Degraded	100	0.180		
	Stopped	0	0.0		
Doors	Degraded	100	0.030	21/79	165/619
	Stopped	0	0.0		
Docking	Degraded	0	0.0		
	Stopped	100	0.790		
GUIDEWAY					
Wayside Communication	Degraded	100	1.000	100/0	626204/0
	Stopped	0	0.0		
CENTRAL MANAGEMENT					
Computer	Degraded	0	0.0	0/100	0/1259
	Stopped	100	0.956		
Communications	Degraded	0	0.0		
	Stopped	100	0.044		

APPENDIX H
DESM INPUT GUIDE

This appendix contains two tables which serve as aids to the user in creating data files for the DESM and in submitting simulation runs. Table H-1 is a form which can be used to conveniently identify the members of partitioned data sets associated with each DESM run. Identifying all the files required for each DESM run helps ensure that all required data files have been created, facilitates job submittal, and provides a record of each run. A member name consisting of up to eight characters must be identified for each file listed in Table H-1. The name should begin with a letter that denotes the model for which it was created and should be descriptive of the analysis being performed. The SOS Software Standards[72] recommend that DESM members begin with the letter E.

The table indicates that up to five demand members containing one or more demand matrices can be specified. If the trip list to be used has already been generated by the DESM Input Processor or by the Deterministic Demand Pre-processor, the STRUC.DEMAND member which contains the trip list is identified, and simulation control parameters are set in the IANDD.RNTIM file to suppress demand processing by the Input Processor. In any case a name for the STRUC.DEMAND member must be supplied. If network processing has already been completed in a previous run of the Input Processor, then the existing member of the STRUC.NETWORK file is identified for input directly to the Model Processor, and an IANDD.RNTIM parameter is set to suppress the network processing in the Input Processor. Otherwise, the name of the STRUC.NETWORK file member to be created by the Input Processor is identified. The Nominal Travel Time, Restart, and Performance Summary files are optional output files which were often not requested during the System Operations Studies. When these files were not to be created by the DESM, the member name was specified as NULL. The INDEX file is a computer record of each simulation run containing a short description of the run and the names of all input and output members.

TABLE H-1. MEMBER NAMES FOR DESM RUNS

Deployment -

DATE ______	JOB ______	DATE ______	JOB ______
IANDD.SYSTEM	______	IANDD.SYSTEM	______
IANDD.DEMAND 1	______	IANDD.DEMAND 1	______
2	______	2	______
3	______	3	______
4	______	4	______
5	______	5	______
IANDD.NETWORK	______	IANDD.NETWORK	______
STRUC.NETWORK	______	STRUC.NETWORK	______
IANDD.RNTIM	______	IANDD.RNTIM	______
NOMINAL TRAVEL TIME-	NULL	NOMINAL TRAVEL TIME-	NULL
INDEX	______	INDEX	______
STRUC.SYSTEM (same as IANDD.RNTIM membername)	______	STRUC.SYSTEM (same as IANDD.RNTIM membername)	______
STRUC.DEMAND (same as first IANDD.DEMAND membername)	______	STRUC.DEMAND (same as first IANDD.DEMAND membername)	______
STRUC.RNTIM	______	STRUC.RNTIM	______
RESTART FILE	NULL	RESTART FILE	NULL
SAMPLE RAW STATS, CHECKPOINT TRIP AND VEHICLE LOG	______	SAMPLE RAW STATS, CHECKPOINT TRIP AND VEHICLE LOG	______
O.P. COMMANDS	______	O.P. COMMANDS	______
PERF.SUMMARY	NULL	PERF.SUMMARY	NULL
JOB DESCRIPTION		JOB DESCRIPTION	

Table H-2 is an input guide which identifies most of the DESM input variables that can be set by the user. Some input variables which were not used in the System Operations Studies or which were introduced as a result of recent software modifications are not included. The input guide identifies variable names, suggested formats, and dimensions as well as a brief description of each variable including the default value where appropriate.

Simulation data contained in the IANDD.SYSTEM and IANDD.RNTIM files as defined in this guide are specified in a generalized input format which allows user defined format specification, constrained by variable type, for the particular data being entered. These data are processed by the Generalized Data Input Processing (GDIP) feature of the DESM which is described in the DESM User's Manual.[12] While GDIP provides a great deal of flexibility in defining input formats, the formats should remain as constant as possible to facilitate the creation of new members. It is convenient to create new members by copying and then editing existing members.

TABLE H-2. DESM INPUT GUIDE

AGT.IANDD.SYSTEM (   )

ECIGL Guideway Link Data

GLHDWY	nF5.0	1 KML
		Minimum headway time in seconds for each link (KML)
GLVEL	nF5.0	1 KML
		Cruise velocity in m/s for each link (KML). If cruise velocity on all guideway links is the same, PSPEED under Service Policy Data can be specified instead of GLVEL.
GLBLK	1i5	
		Fixed headway block length in meters. Required only for fixed block headway regulation (POLVPR=1)
GLVSD	1F5.0	
		Standard deviation of vehicle speed on guideway. Can be specified only for asynchronous control.
GLRTIM	1F5.0	
		Acceleration reaction time for dequeing from guideway links. Default value is 0.

ECIPOL Policy Data

POLVPR	1i5	
		Vehicle headway protection scheme 1 = fixed block 2 = variable headway (default)
PTSPLT	1i5	
		Trip split size - number of passengers comprising subgroups into which trips should be split if a trip cannot fit in the available space on a vehicle. The value should be less than or equal to the vehicle capacity. If it is greater than the maximum trip size, trips will not be split.

POLSER	1i5	
		Service Policy 1 = Demand responsive single party 2 = Demand responsive multi-party 3 = Scheduled service
PXFER	1L1	
		Transfer Policy F = No transfer (default) T = Transfers
PVSPAC	1i5	
		Vehicle Spacing Algorithm 1 = Fixed departure time (default) 2 = Midpoint dispatching
PRTDEF	1i1	Source of route definition in scheduled service 0 User defined routes (Default) 1 Routes generated by 1.P.(cyclic)
PVRLST	ni3	1 KNRT
		Scheduled Route List List of station entry nodes comprising each route. Each route is separated by a zero KNRT = number of entries in the list including zeros.
PRASGN	ni2	1 KNS 1 KNS
		Route Assignment Table Matrix of route numbers where first KNS entries give the route used to start a trip to station 1 from the KNS stations in the network. (Input in column order). A route number greater than KNRT refers to a group of routes that serve the O/D pair.
PRGLST	ni2	1 KMGT
		Route Group List List of route numbers comprising each group of routes. Each group is separated by a zero. KMGT = number of entries in the list including zeros.
	PWALKT	1i5
		Transfer walk time in seconds Input only if PXFER = T.

PXFLST	12i5	1	4	1	KMXFER

Transfer Station List
A four element parameter which identifies the station entry node at which the first transfer is made for trips between O/D pairs that require one or more transfers.

Element (1,i) entry node number of origin station

Element (2,i) entry node number of destination station

Element (3,i) entry node number of station at which deboard occurs

Element (4,i) entry node number of station to walk to before reboarding.

KMXFER = number of O/D pairs for which a transfer is required. List is input only if PXFER = T

POLLC 1i5

Longitudinal Control Policy
1 Synchronous
2 Quasi-synchronous (single vehicles only)
3 Asynchronous (Default)

POLDIS 1i5

Dispatch Policy
1 Deterministic
2 Quasi-deterministic
3 Non-deterministic (default)
Must be compatible with POLLC.

POLMRG 1i5

Merge Policy Indicator
1 FIFO (Default)
2 Maneuvers based on delay table
3 Priority

NLNPRi ni5 1 (No. of node pairs in table)

List of node pairs defining the links that have priority at merges. Odd subscripts = node at beginning of link; even subscripts = node at end of link. Input required only if POLMRG = 3

PMRGL	4i5	1 2 1 2 Local Merge Priority Table Element 1 Priority of empty vehicle on guideway Element 2 Priority of full vehicle on guideway Element 3 Priority of empty vehicle in station Element 4 Priority of full vehicle in station Value of 1 is highest priority Default: 2, 1, 4, 3 Input only for off-line stations (STYPE = T)
PARMAX	1i5	Maximum vehicle maneuver at merge in terms of number of slots. Input only for quasi-synchronous control (POLLC = 2)
PADVNC	1i5	Vehicle advance maneuver indicator 0 No advance >0 Advance permitted Input only for quasi-synchronous control (POLLC = 2)
PMRGWW	1F5.0	Merge reservation table window width in seconds. Input only if POLLC = 2.
PMRGTH	1F5.2	Fraction of merge window to be reserved Input only if POLLC = 2
PVRES	1L1	Logic variable to indicate if vehicle reservations are allowed. F = No reservations (default) T = Reservations allowed Input only if demand responsive service (POLSER = 1 or 2)
PVDVRT	1L1	Vehicle diversion from guideway to board trips when station is not vehicle destination F = No diversion T = Diversion permitted (Default) Input only for demand responsive service

PENTS 1L1

Logic variable to indicate static (in station) entrainment is to be done.
  T = Entrainment
  F = No entrainment (Default)
Input only for demand responsive service

PENTD 1L1

Logic variable to indicate dynamic (on guideway) entrainment is to be done.
  T = Entrainment
  F = No Entrainment (Default)
Input only for demand responsive service with asynchronous control.

PMXTRL 1i5

Limit on the number of vehicles in a train (0 = no entrainment, 1 = Default) Input only if PENTS and/or PENTD = True.

PNTRLM 1i5

Maximum wait time for entrainment in station in seconds. Default is 15s. Input only if PENTS = T.

POLDMS 1L1

Demand stop indicator
  F = stop at each scheduled stop (default)
  T = stop only if demand exists
Input only for scheduled service and for control other than synchronous.

ECNPOL Service Policy Data

PLOSBS 1i5

Source of level of service spec.
  0 User input (PNVRTE or PRTEHW)
  n I.P. calculates level of service based on the nth demand matrix in demand file.

PLDFAC 1F5.0

Estimated achievable vehicle load factor (ratio of occupancy to capacity). Input only for demand responsive multi-party (POLSER = 2) and computed level of service (PLOSBS = n).

PSPEED 1F5.0

Nominal vehicle speed for all guideway links unless over-ridden by GLVEL in m/s

ECICFG Station Configuration Data

SLVEL 1F5.0

Station Link Velocity in m/s

SLBVEL 1F5.0

Speed of vehicle through an online station if no stop is required. m/s
Default is GLVEL. This value should be specified so that the desired net travel time through the station is (SLVEL/SLBVEL)* (SL travel time).
SL travel time is specified in SLCFIG or is calculated using SLVEL.

SLCFIG 13F5.0 1 13 1 KNSL

Station link characteristics for each of KNSL station links

TYPE TT LL CAP EV1 EV2 EV3 EV4 EV5 FN0 ORD HT ET

SLPF ni5 1 KNSL

DQ from upstream SL's in FIFO or priority order
- 0 FIFO (Default)
- 1 PRIORITY

If priority, then list links in order in SLCFIG.

Comments on SLCFIG parameters

Station Link Type	Events
1 Input Ramp	1 Headway
2 Input Queue	2 Travel
3 Dock	3 Deboard
4 Output Queue	4 Board
5 Output Ramp	5 Store
6 Storage	6 Launch
7 Input to Storage	
8 Storage to Input	
9 Dock to Storage	
10 Storage to Output	

Specify travel time (TT) or length (LL); not both

TT = Total link traversal time minus headway time

FN = Diverge Function

ORD = Order of dequeuing from station links

HT = Headway time per train in seconds
Total headway zone travel time = H_T + ET * No. cars per train

ET = Headway time per vehicle in seconds

SLAVAL nL1 1 KNSL 1 KNS

Indicates whether SL is available
F Not available
T Available (default)

PBERTH 1i5

Berth assignment policy
1 To most downstream available berth ASAP
2 Form platoons, send when berth area clear.

ECISTN Station Data

SBQCAP ni5 1 KNS

Boarding Queue Capacity
If the boarding queue reaches capacity, trips are turned away and not processed by the sim.

STDBA 1F5.0

Deboard time per passenger in seconds

STDBB 1F5.0

Deboard time in seconds

STBA 1F5.0

Board time per passenger in seconds

STBB 1F5.0

Board time

STBMAX	1F5.1	
		Maximum boarding time Default = time to fill an empty vehicle
STYPE	1L1	1 KNS
		Type of Station F Off-Line (Default) T On-Line (only if POLLC = 3)
PALTET	1i5	
		Alternate station egress time in seconds

ECISYS Simulation System Data

AKSEED	1i5	
		Random number seed - any odd number greater than 3. 14825 - Default
ASAMPi	1i5	
		Sampling interval in seconds
ASTATU	1i5	
		Samples per snapshot report
CSIZE	1i5	
		Clock units per minute. Default is 60
CLOOP	1i5	
		Number of entries per clock table entry. Default is KMX-KMT
CLSMAL	1i5	
		Increment in time between successive clock table intervals. Default is 100.
CLSIZE	1i5	
		Number of entries in clock table. Default is KMCLTA.

Empty Vehicle Management (Input the following variables only for demand responsive service)

PVSPR	i5	1 KNSVP	Ordered list of where to look for empty. PVSPR(1) - First place to look, PVSPR (KNSVP) = Last place to look.
PEVALM	1i5		Empty vehicle arrival time limit in seconds. Input only if PVSPR = 1, 5, 6, or 7, is specified in the list.
PSLIST	ni5	1 KNSL	List of station link types where empty is to be looked for. KNSL = Number of station link types in the list. Input only if PVSPR = 2 is specified in the list.
PSRCFM	ni5	1 KNS	The entry node number of the station that acts as the regional center from which each station gets empties. Input only if PVSPR = 4 is specified in the list.
PVEPR	ni5	1 KNEVP	Ordered list of where to send an empty vehicle. PVEPR(1) = First place to try, PVEPR(KNEVP) = Last place to try.

PVSPR values:

Values	Place
1	A non-circuitous vehicle about to arrive/bypass the station
2	Use PSLIST
3	Local storage
4	Regional storage
5	An empty circulating on the guideway
6	Earliest available
7	Any expected arrival

Default is 6

PVEPR values:

Values	Place
1	Local storage
2	Regional storage
3	Distribute according to anticipated need without considering current availability of empties
4	Distribute according to anticipated need while considering current availability of empties

		5	Circulate on the guideway on a predetermined route
		6	Circulate to next best station--one with most requests
		Default is 1,3	

PSRCTO ni5 1 KNS

Entry node number of the station that acts as the regional center to which each station sends empties. Input only if PVEPR = 2 is specified in the list.

PANEED ni5 1 KNANT

Concatenated list containing a sublist for each station. Each sublist contains the anticipated number of empty vehicles needed at the corresponding PANSTN entry. A value is required for each station with a zero defining the end of the station entries. KNANT = number of entries in the list. Input only if PVEPR = 3 or 4 is specified and user defines level of service (PLOSBS = 0).

PANSTN ni5 1 KNANT

Concatenated list containing a sublist for each station. Each sublist contains the entry node number of stations to which each station is to send empty vehicles. KNANT = the number of entries in the list and must also equal the number of entries in PANEED. Input only if PVEPR = 3 or 4 is specified and user defines level of service (PLOSBS = 0).

PECRTE ni5 1 KNCRS

Circuitous Empty Vehicle Route List of station entry nodes comprising each empty vehicle circulation route. Each route is separated by a zero. Input only if PVEPR = 5 is specified in the list.

PECRTN ni5 1 KNS

Number of the empty vehicle circulation route onto which each station sends empties. Input only if PVEPR = 5 is specified in the list.

PATH SELECTION

PSMETH	1i5	
		Path selection method 1 A priori (in the station) - default 2 Real time (at diverge) Choice valid only for asychronous, non-deterministic, and single party demand responsive or scheduled.
PSTYPE	1i5	
		Path selection method 1 Table look-up (default) 2 Algorithmic Choice valid only for single party demand responsive or scheduled.
PSALGM	1i5	
		Path selection algorithm indicator 1 Nominal travel time (default) 2 Link length 3 Utilization 4 Weighted combination of 1 and 3
PSTWT	1F5.0	
		Weighting factor for nominal travel time for algorithmic path selection.
PSUWT	1F5.0	
		Weighting factor for utilization for algorithmic path selection.
PALTHT	ni3	1 KNALT
		Alternate path node sequences. Concatenated list containing a sublist for each common diverge point. First entry in each sublist is node 1.0 of destination station. This is followed by a sequence of nodes defining the path. If more than one alternate path to the same destination from the same common diverge, separate node sequences by -1. Each sublist ends with Ø.
PMDWT	1F5.0	
		Weighting factor for merge scheduling delay for alternate paths with either deterministic or quasi-deterministic dispatch.

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O.TEXT

O.OPTION

NEWNET 1L1

Is a new STRUC.NETWORK file to be generated?
T = yes
F = no

NCSEL 1i1

Selection of cost for least cost path determination
0 Use link travel time
1 Use link length

DTRPFL 1L1

Is a new STRUC.DEMAND file to be generated?
T = yes
F = no

ANOMTT 1L1

Nominal travel time file request
T = Write file; F = Do not write file (Default)

ATRPLG 1L1

Trip Log File Request
T = Write trip log file
F = Do not write trip log file (Default)

O.DATA

DMPROF 3F 8.0 1 3 1 KMDPRF

Demand Scaling Profile
Element (1, i) Scale factor for i^{th} interval
Element (2, i) Time base for the i^{th} interval (if 0, the time base stored with the matrix is used)
Element (3, i) Matrix indicator
0 Use matrix currently in memory
>0 read a new matrix
KMDPRF is the number of demand profile intervals to be processed.

DNDMND	1i5	Number of demand profile intervals to process Enter zero is DTRPFL=F
ATREAD	1i5	Time to begin reading trip records in seconds from start of simulation
VCAP	1i5	Vehicle capacity in passengers
VSEAT	1i5	Number of seats per vehicle Default is VCAP
VLEN	1i5	Vehicle length in meters
PNVRTE	ni5	1 KNR Number of vehicles per route. If level of service is user specified (PLOSBS = 0), PNVRTE must be specified <u>unless</u> PRTEHW is specified.
PMAXWT	1i5	Maximum wait time in seconds that a person should wait for a vehicle in scheduled service. Input only if I.P. computes level of service. Default value is 900s.
PRTLEN	ni5	1 KNR Number of vehicles per train on each route (0 = no trains)
PRTEHW	ni5	Headway of vehicles on the same route If level of service is user specified (PLOSBS = 0), either PRTEHW <u>or</u> PNVRTE must be specified.
KNV		1i5 Number of vehicles available for service. Input only for user defined level of service demand responsive.

PHiST1 1i5

First threshold for excess travel time histogram in seconds. Default is 300s.

PHiST2 1i5

Second threshold for excess travel time histogram in seconds. Default is 900s.

AVLOG 1i5

Indicates if vehicles are to be logged as they approach a station
- 0 = no log required
- N = log vehicles as they arrive at station entry node N.

ACKPTi 1i5

Periodic checkpoint interval in seconds.

END

0.INDEX

DESM USER ID DATE

XXXXX.CKPT

Write a checkpoint file at XXXXXs after the start of the simulation.

XXXXX.AFSM

Perform active fleet size management at XXXXXs after the start of the simulation. Follow this card by redefinition of KNV for demand responsive or PRTLEN and PNVRTE for scheduled

XXXXX.FAIL			
		Fail an entity or recover from a failure at XXXXXs from start of run.	
AFALRE	nF5.0	1	n
		Failure or recovery details n = 5 or 6	
XXXXX.STOP			
		STOP the simulation after XXXXX seconds of simulated time.	

APPENDIX I
REPORT OF NEW TECHNOLOGY

Work performed by GM Transportation Systems Center under contract DOT-TSC 1783 in the area covered by this report resulted in the development of a generalized procedure for analyzing Automated Guideway Transit (AGT) system deployments using the System Operations Studies (SOS) software.

An analysis procedure has been developed which can be used to establish three increasing levels of detail in the design requirements and/or specifications for AGT system deployments.

The first step of the procedure established an approach for defining system level requirements of the application area using either site specific information or deriving the requirements based on generic information generated during the SOS program.

The second step of the procedure suggests major design option trade-off analyses that can be performed to enable the analyst, through simulation and analytical methods, to arrive at a more detailed set of system level design parameters when considering performance, cost, and availability requirements or objectives.

The third and final step of the procedure develops an analysis approach which utilizes sensitivity analysis to further refine the individual system design parameters.

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